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The Feasibility of Developing Forecast Systems to Predict Changes in Beach Sand Volume on Ocean Beaches during Storms

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THE FEASIBILITY OF DEVELOPING FORECAST SYSTEMS TO PREDICT CHANGES IN BEACH SAND VOLUME ON OCEAN BEACHES DURING STORMS

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APPROVAL SHEET

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ABSTRACT

Sixteen beach transects along the open ocean coast of Virginia were monitored for a period of 20 months to determine the feasibility of developing a system to forecast changes in beach sand volume resulting from storm conditions. The investigation was limited to systems that would require easily obtained variables as predictors. An examination of factors known to influence beach modification indicated that for prediction purposes, only wind characteristics, the ocean-still-water-level, and the initial beach condition need consideration. The initial beach condition, crudely quantified as the cross-sectional area of sand between the beach surface and a reference base line, was shown statistically to be a strong factor in determining the character of the beach change. Knowledge of the initial beach condition, however, is not always readily available and it was omitted from further considerations.

An empirical prediction model utilizing wind values at NMC (National Meteorological Center) grid points and water-level at given locations as predictors was developed using a linear regression screening technique. Results indicated that it may be possible to develop prediction equations to forecast beach changes for sections of ocean beach that do not exhibit complex offshore bathymetry.

The relation between beach volume changes, at various locations, and common storm-energy inputs was examined to determine whether beach changes at a given "indicator transect" could be used to predict beach changes at other locations. This seems a promising possibility. The study demonstrated the operational problems and indicated the research needed in this field in which little work has been done.

THE FEASIBILITY OF DEVELOPING FORECAST SYSTEMS
TO PREDICT CHANGES IN BEACH SAND VOLUME ON
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INTRODUCTION

At the land-sea interface, a beach acts as an energy absorber, dissipating the kinetic energy of waves through the mechanism of sand transport. Typically, during times of high energy input, sand is removed from the beach and deposited offshore (King, 1959). This process is reversed during low-energy conditions, and the beach is built up. During severe storms, this balance may be upset. Large waves, high winds, and an abnormally high water level may combine to remove a critical amount of sand, and do extensive damage to natural features and man-made structures. Many such cases have been cited in the literature with property damage running into the millions (see Johnson, 1919; Hardy, 1962; and Truitt, 1968).

Considering the magnitude of the population concentrated on the world's sea coasts, it seems imperative that methods be developed to predict, accurately and regularly, changes that will occur in a beach face for a given set of ocean-atmosphere conditions. At present, predictions are possible only in a qualitative way, by an experienced investigator familiar with a given stretch of beach who employs the "educated guess" method.

Investigations by Shepard (1950), Inman (1953), and Ziegler, Hayes, and Tuttle (1958) have dealt with measurements taken before and after storms. These measurements were related in a qualitative manner to the causal forces of winds, water levels, and waves. Considerable progress has been made in predicting the major destructive forces of a storm;

wind (Shuman and Hovermale, 1968), waves (Bretschneider, 1967, Pore, 1969), and water-level (Pore, 1970, Harris and Angelo, 1963), but the author knows of no attempt to obtain a quantitative forecast of beach change for ocean-storm conditions.

The goal is to obtain fast and accurate predictions concerning the magnitude and location of impending beach modification. To do so, the prediction system must be easily incorporated into existing forecasting schemes, and the predictors must be;

1) available through routine observation and prediction, and
2) the predictors themselves must be reliably predictable.

These criteria exclude the use of predictors representing such local phenomena as surf characteristics, except as may be determined for a selected indicator site, and dictate the use of data for atmospheric and open-ocean parameters, such as wind and deep-water wave characteristics.

The text that follows is devoted to examining the feasibility of developing a prediction system for significant changes in a beach face under high-energy, storm-wave and storm-surge conditions.

The approach includes:

1) evaluation of variables of the beach-ocean-atmosphere and their order of importance for prediction purposes,
2) construction and testing of an empirical prediction model,
3) examination of alternative prediction systems, and
4) determination of research needed for the development of effective prediction methods.

SETTING OF THE STUDY

Study Location

The study dealt with the open ocean beaches of Virginia and storm activities affecting them. Figure 1 shows the area of general concern and the position of the beaches monitored in relation to the overall study area.

Sixteen permanent beach-profile transects were established along Virginia's open ocean coast (Fig. 2). Shoreline trend and relative positioning of the sampling transects on each beach may been seen more clearly on Figures 3 through 7. The beaches were divided roughly into two types, barrier beaches and mainland beaches. The beaches north of the mouth of Chesapeake Bay (transects 1 through 10) are located on barrier islands. These islands are separated from the mainland by an extensive area of salt water marsh. The islands are migratory in nature and the sand beach is underlain by old marsh bed. The profile stations south of the mouth of Chesapeake Bay are located on the mainland and are part of a continuous beach running from Cape Henry to the barrier island system that forms Cape Hatteras, North Carolina.

Characteristics of the Study Area

The individual characteristics of the beach at each profile sampling station are shown in Table 1.

Tides in the study area are semi-diurnal with slight diurnal inequalities. False Cape, beach transect 15, at the southern end of the

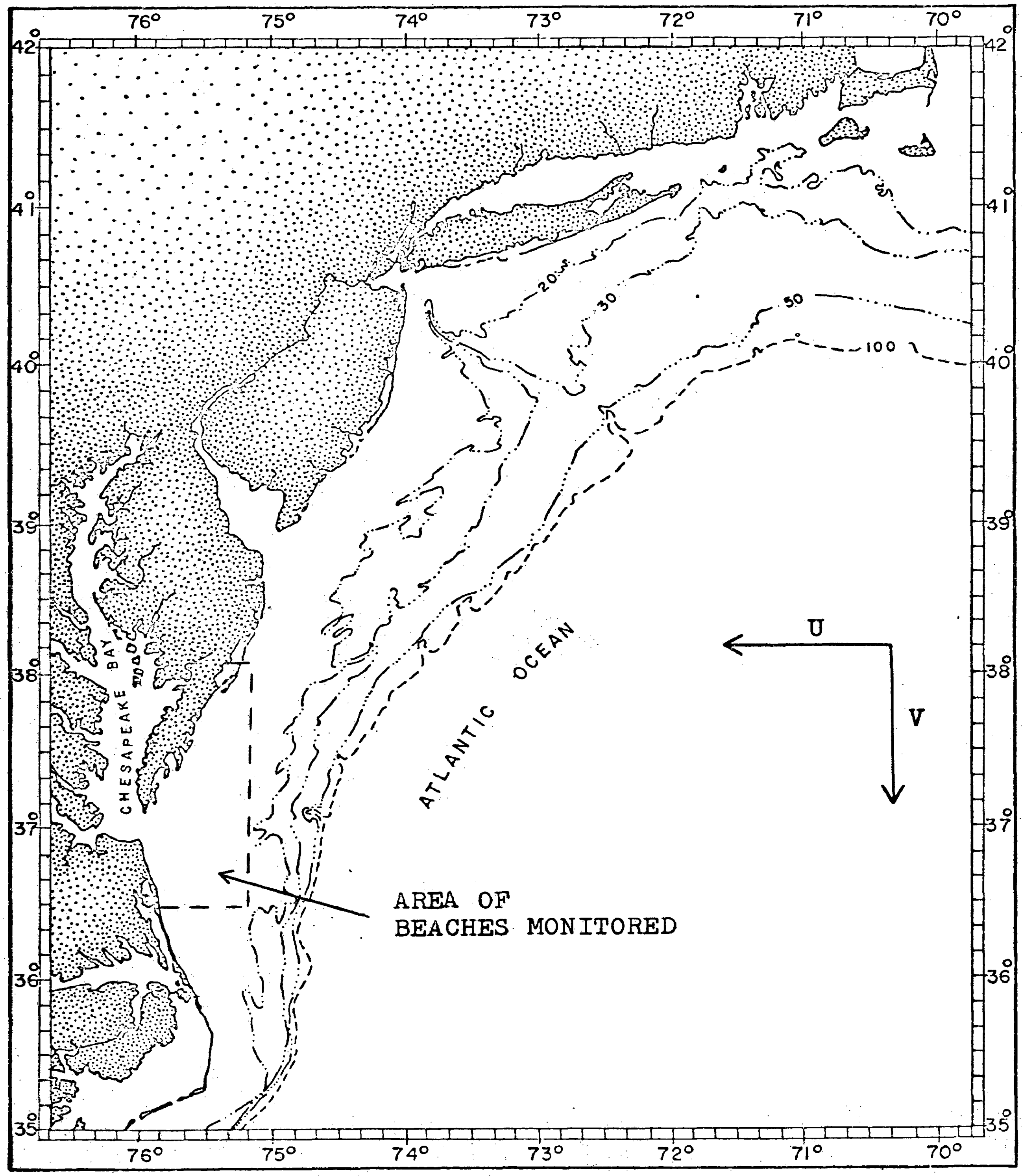


Fig. 1. General study area.(depth contours in fathoms).

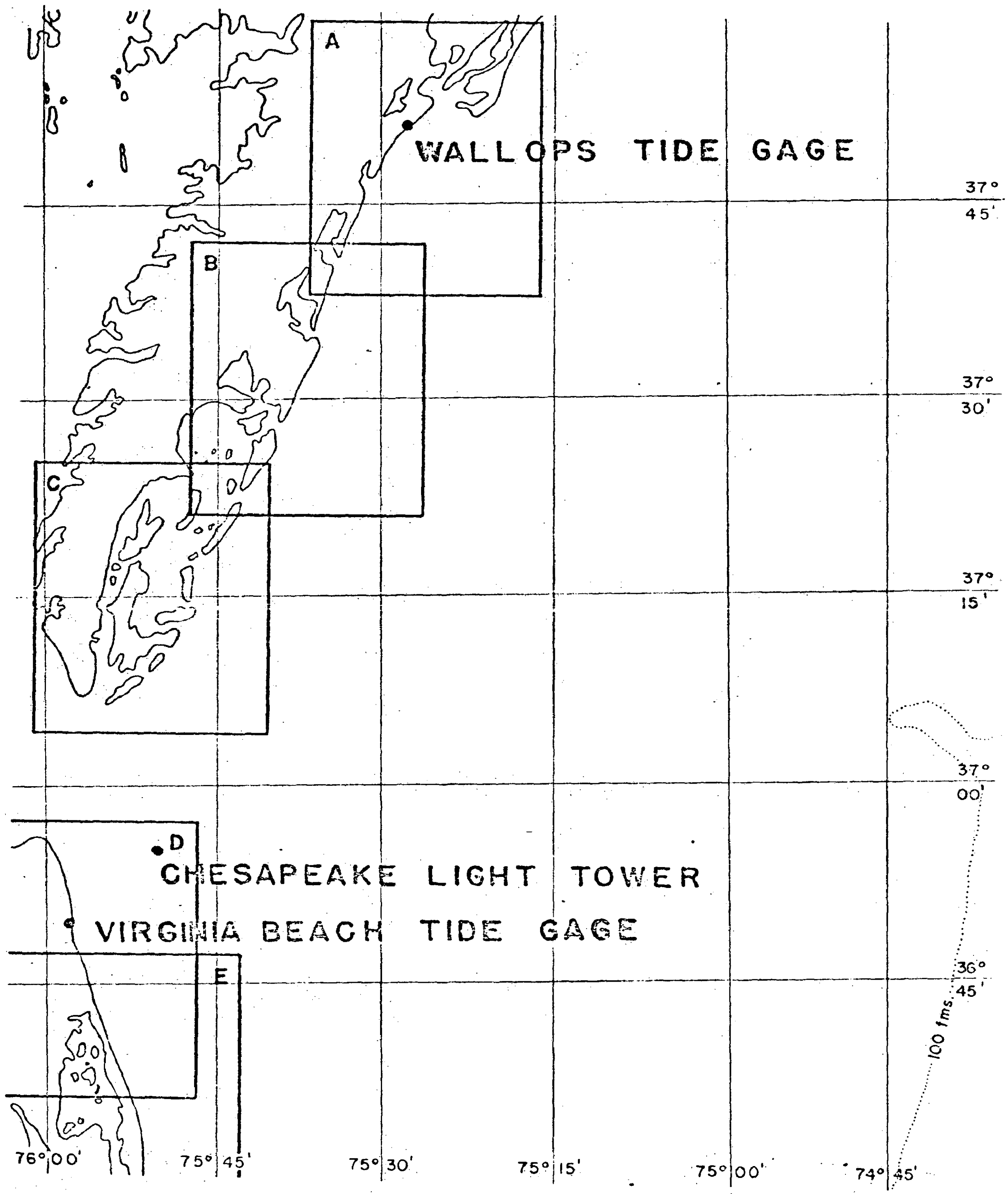


Fig. 2. Area of beaches monitored and guide to the relative positions of the beach transects.

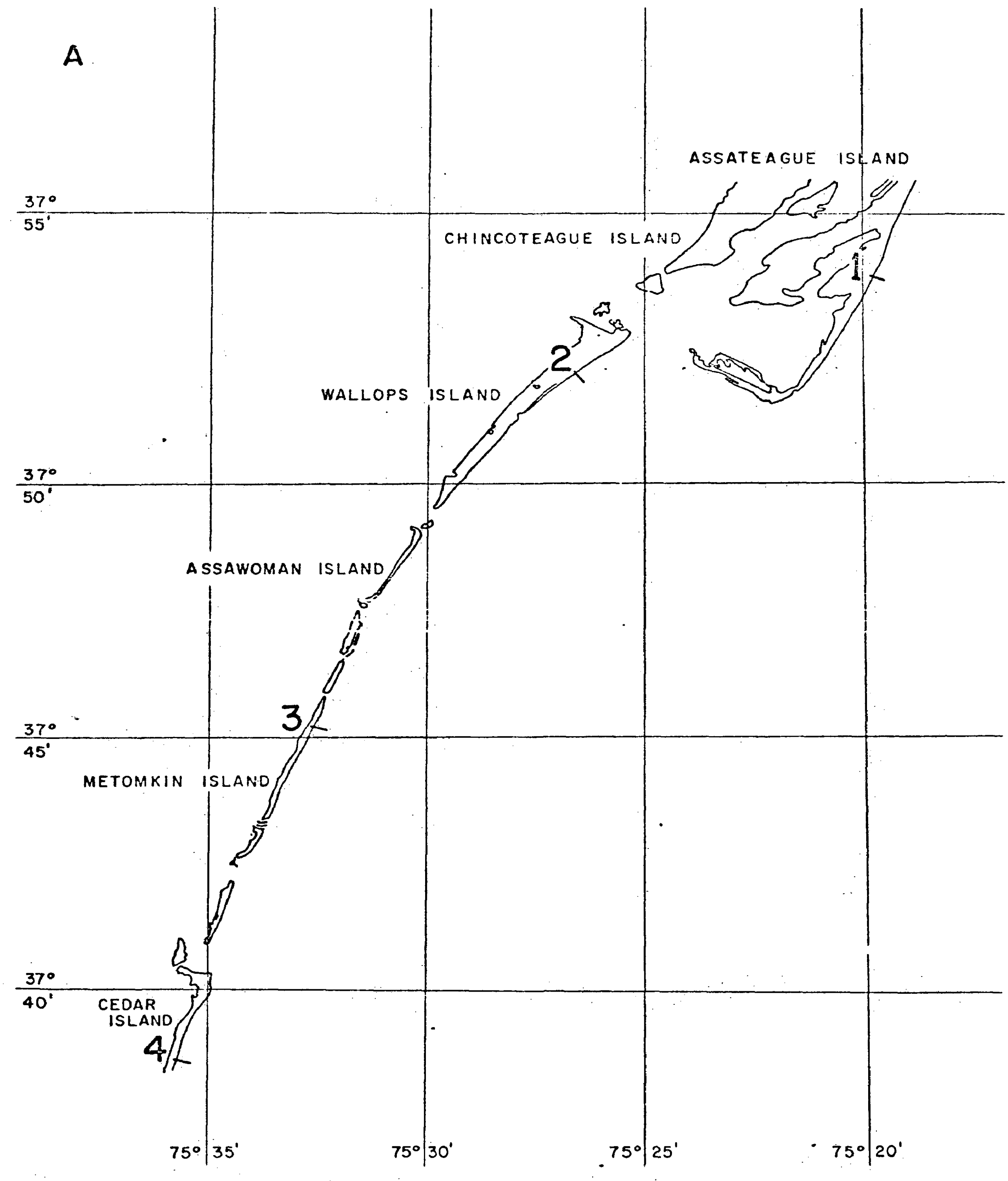


Fig. 3. Transects 1 thru 4.

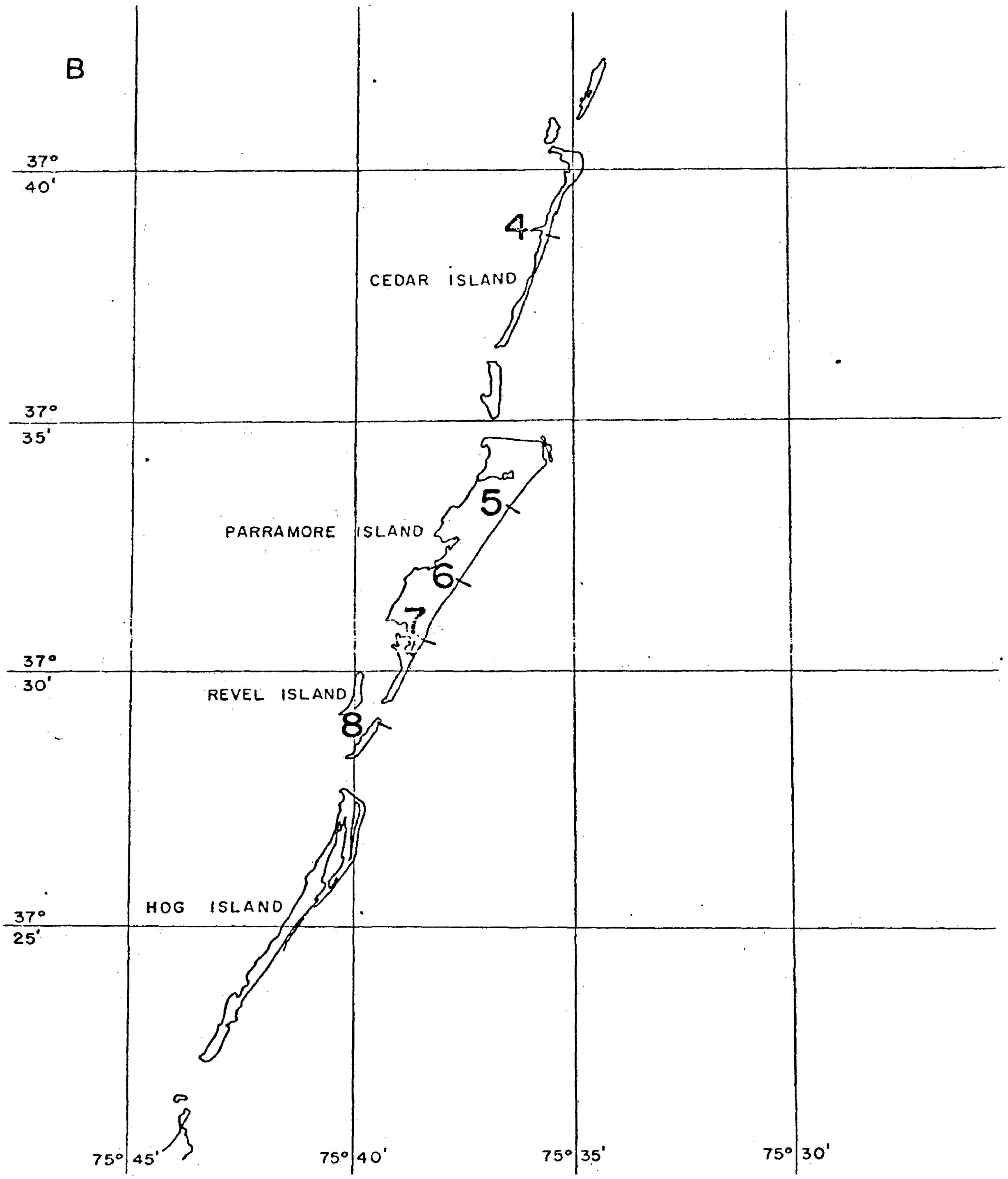


Fig. 4. Transects 5 thru 8.

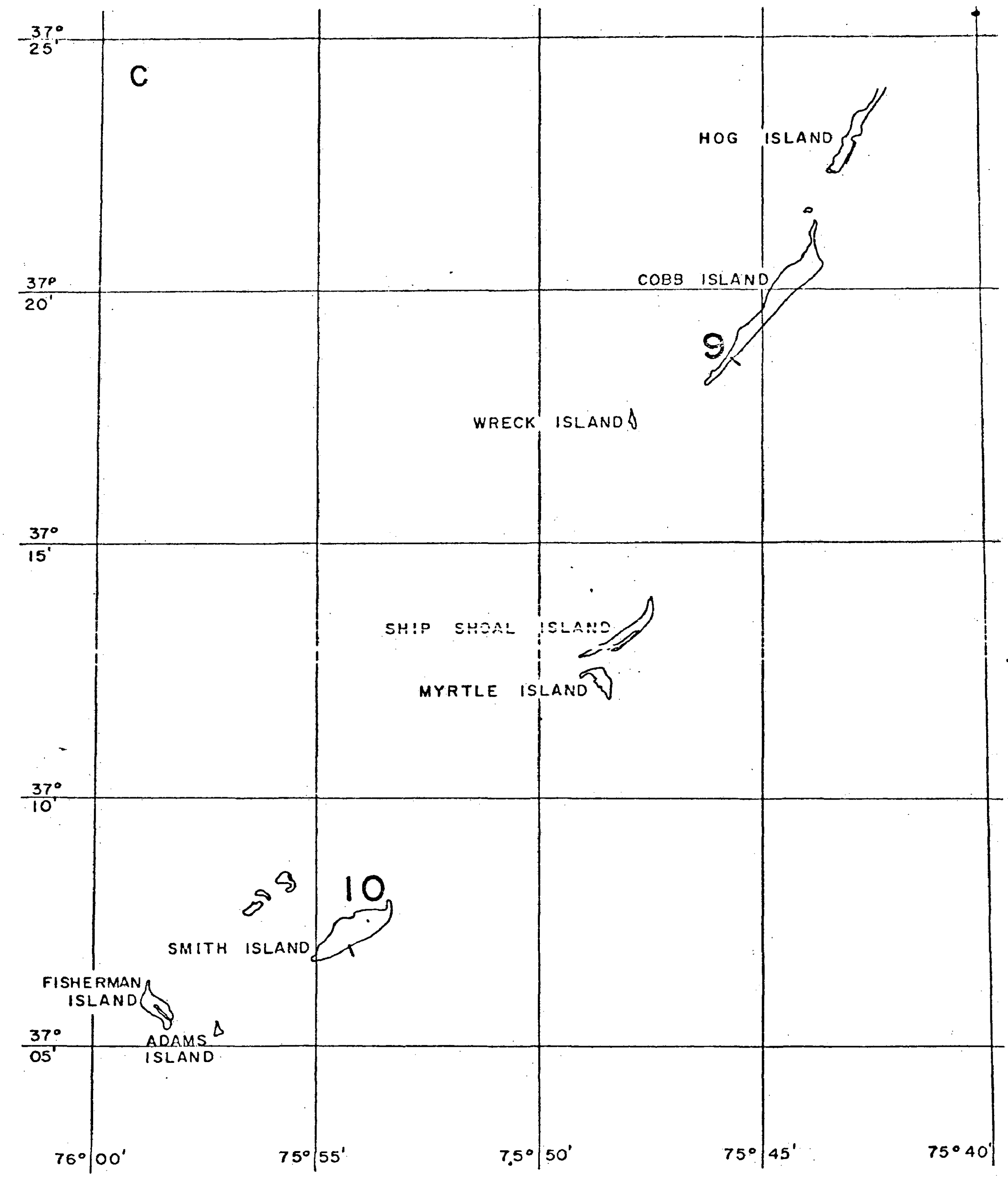


Fig. 5. Transects 9 and 10.

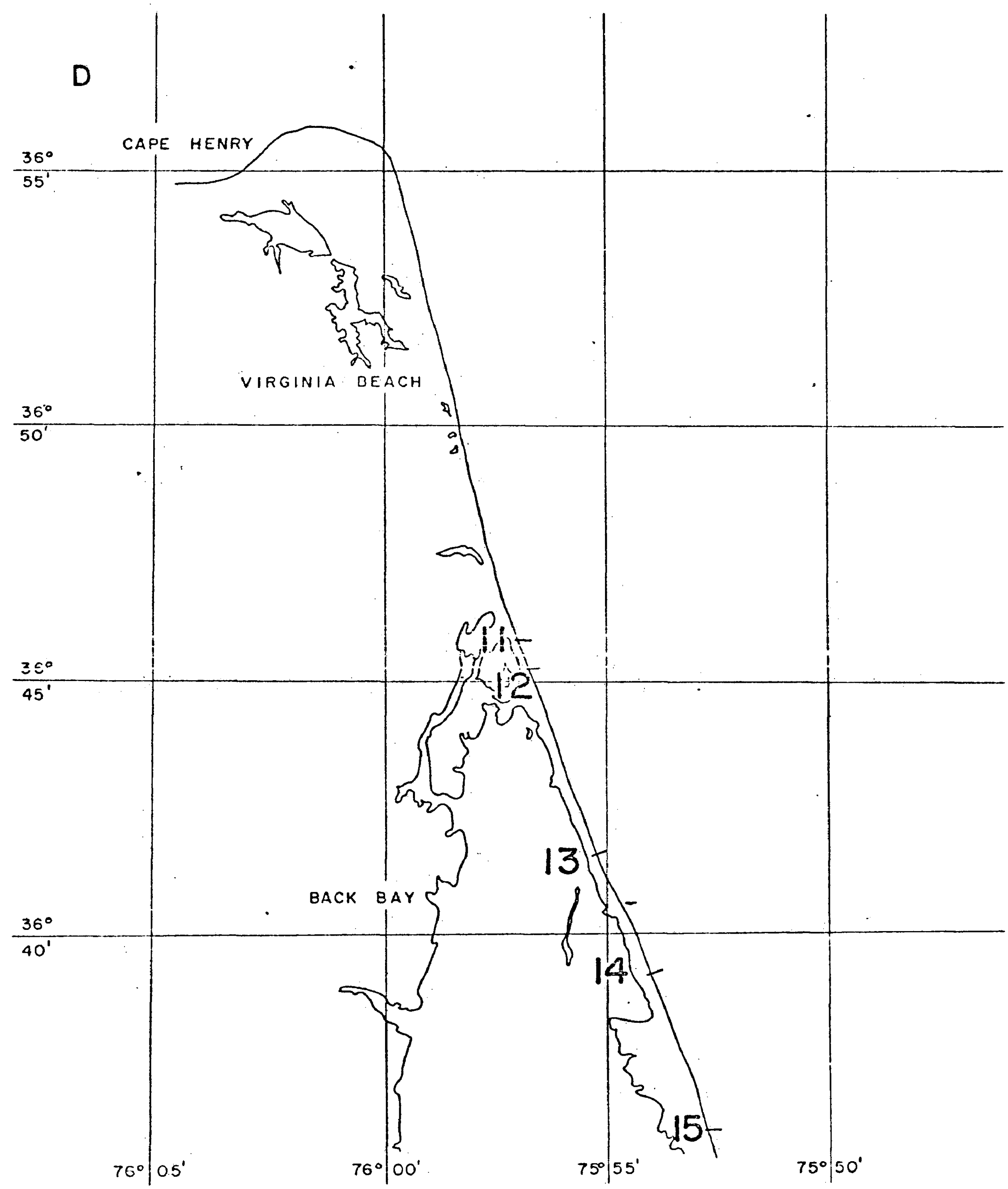


Fig. 6. Transects 11 thru 15, and the coastline trend below Cape Henry.

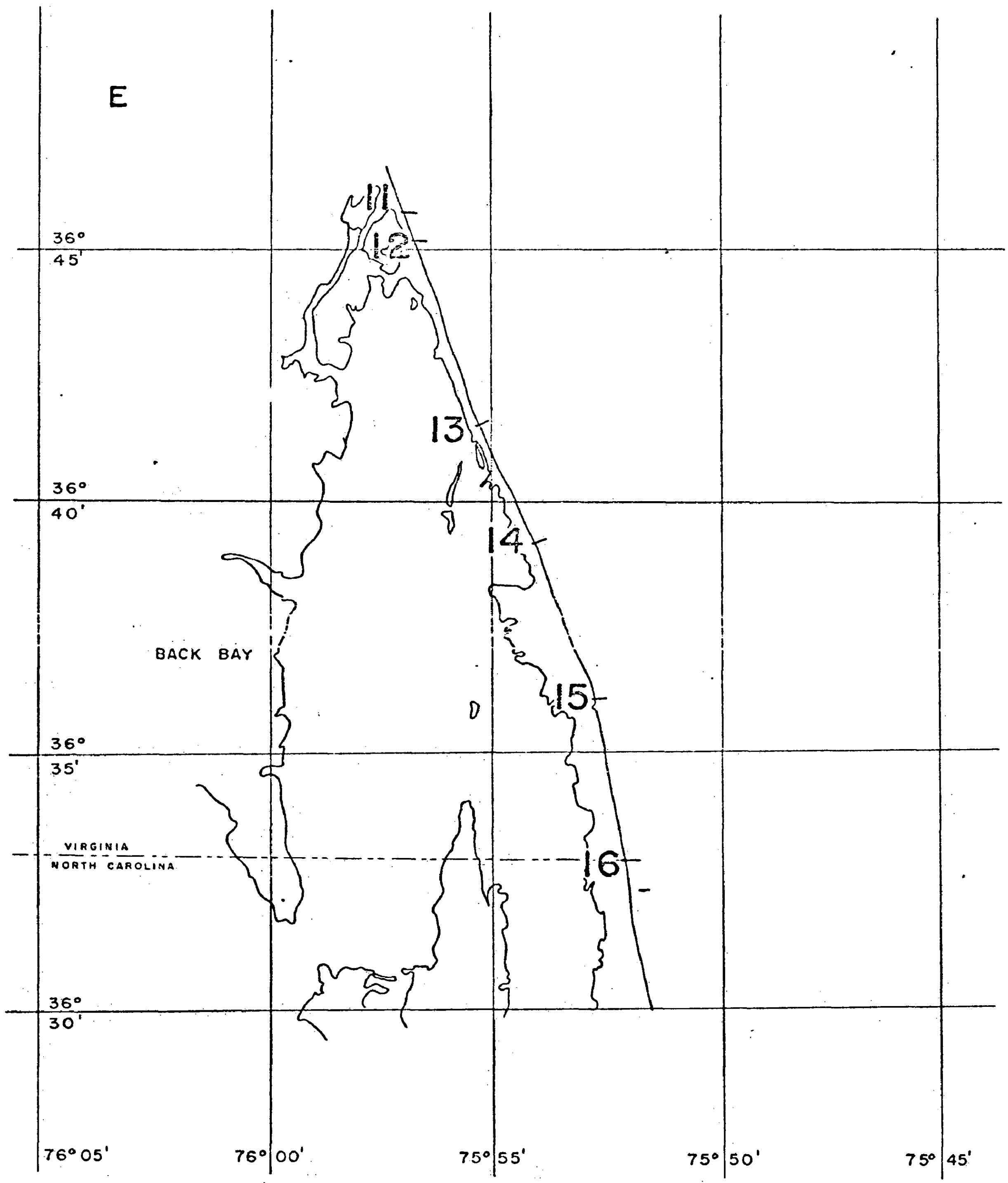


Fig. 7. Transects 11 thru 16.

Table 1. Characteristics of the beaches monitored.

Transect	Approx location	Sand* grain diam (mm)	Shoreline trend (degress from true north)	Mode foreshore slope (degress)	Remarks
1	$37^\circ 54.1'$N $75^\circ 19.6'$W	.150	23°E	5.5	straight beach, on Assateague(barrier isle)
2	$37^\circ 52.2'$N $75^\circ 26.3'$W	.094	53°E	1.5	Wallops Isle, barrier beach concave to ocean, in lee of Assateague to NE
3	$37^\circ 45.2'$N $75^\circ 32.8'$W	.130	25°E	1.2	Metomkin Isle, barrier beach, straight
4	$37^\circ 38.8'$N $75^\circ 35.7'$W	.155	19°E	2.5	straight beach, on Cedar Isle
5	$37^\circ 33.3'$N $75^\circ 36.3'$W	.105	30°E	1.7	near headlands on Parramore Isle, slightly convex to ocean
6	$37^\circ 32.5'$N $75^\circ 37.4'$W	.098	30°E	1.1	slightly concave to ocean on Parramore Isle
7	$37^\circ 30.6'$N $75^\circ 38.2'$W	.105	30°E	1.5	concave to ocean on Parramore Isle
8	$37^\circ 29.0'$N $75^\circ 39.4'$W	.110	28°E	1.1	near end spit on Parramore Island, subject to severe washover during storms
9	$37^\circ 18.7'$N $75^\circ 45.6'$W	not sampled	40°E	1.7	straight beach on southern tip of Cobb Isle

* Mean grain diameter as determined by Wentworth seive series, samples collected after storm conditions in the foreshore.

Table 1. (con't) Characteristics of the beaches monitored.

Tran-sect	Approx location	Sand* grain diam (mm)	Shoreline trend (degress from true north)	Mode fore-shore slope (degress)	Remarks
10	37°07.0'N 75°54.2'W	not sampled	60°E	1.8	near spit end on Smith Isle
11	36°45.9'N 75°56.9'W	.210	13°W	1.0	straight beach, but located at the base of concave curve
12	36°45.2'N 75°56.8'W	.210	15°W	1.9	slightly concave to ocean
13	36°41.6'N 75°55.2'W	.210	18°W	1.1	concave to ocean
14	36°39.2'N 75°54.1'W	.210	23°W	1.2	convex to ocean
15	36°36.1'N 75°52.8'W	.210	17°W	1.3	False Cape, convex to ocean, offshore ridges
16	36°33.0'N 75°52.0'W	.210	9°W	1.2	straight beach

* Modal grain size, interpolated from berm samples taken by Swift et al. (1971).

study area, has a mean tidal range of 1.2 m and a spring tide range of 1.4 m. Tide levels at the other beach transects are close to the False Cape values.

The study area is highly susceptible to storm conditions. Bosserman and Dolan (1968) report, on the basis of a survey of storms over a 20 year period, that generally about 12 storms a year with severe beach eroding potential can be expected. March and November have the greatest number of destructive storms. The storm frequency survey was made with respect to beach erosion at Cape Hatteras, (approximately 150 km from the southern tip of the study area). However, the storms surveyed were synoptic in scale, and the typical storm track trended into the study area.

Physical Considerations During the Study

The study was conducted from July, 1969 to March, 1971. During this period wind-wave activity at Chesapeake Light (Fig. 2) ranged from a calm sea to wave heights of 7 m during storm conditions. Wind-wave frequency analysis showed the majority of waves ranged between 0.5 and 1.5 m in height. The wind-wave period was 2 seconds during 73% of the study.

During the study period, 41 storms generated wind-wave heights at Chesapeake Light of 2 m or more, about half of these could be considered major storms, generating wind-waves of at least 2.5 m. Storm surge (actual ocean-still-water-level minus predicted tide level) of 0.2 to 0.6 m were characteristic of the majority of the storms.

DATA COLLECTION AND REDUCTION

Dependent Variable: Change in Sand Prism

Beach Profiles - Beach profiles were taken when storm conditions seemed imminent, as determined by weather forecasts obtained from the National Weather Service. Beaches were then profiled following relaxation of storm conditions, if the initial forecasting proved correct. In any event, profiles were taken once a month, except that, during winter months, no profiles were taken at transects 9 and 10 (Fig. 5).

An articulated-frame profiler and a tape recorder were used in profiling. This equipment has the advantage of allowing rapid profiling by only one individual. It yields profile data with an acceptable degree of accuracy. The system allows portability and rapidity of measurements.

Basically, the profiler consists of a square frame hinged at each corner so as to be deformable to any requisite parallelogram. The calibrated base member of the frame lies on the beach. The slope of the beach is read as the angle made by the horizontal upper member and one of the tilted upright members using a bubble-level protractor system. In this manner consecutive pairs of slope angle and beach length are accumulated for a given profile station.

The raw data in final form consist of a series of polar-coordinate pairs, A (angle) and R (radius), each using the prior pair as the origin. A set of computer programs was developed to transform the polar coordinates into rectangular coordinates, to compute beach sand-volume changes occurring between profiling dates, and to plot the beach profiles. These programs are discussed fully in Appendix A.

The profiling frame was calibrated in centimeters and had a base length of 1.5 m. Angles were recorded to the nearest tenth of a degree, positive down from the horizontal when looking north (sea to right, land to left).

Beach transects were marked at the landward end by two vertical pipes emplaced in the backshore dune which formed a line normal to the coast. A reference elevation was marked on the pipes. In profiling, the elevation of the beach, relative to the reference mark was recorded at the onset of profiling.

A line perpendicular to the shore, running from the swash zone to the reference pipes, was determined by orienting the base of the profiler on an imaginary line defined by the two reference pipes. Each beach-slope and base-length pair was voice recorded using a tape recorder. Immediately after profiling, the tape recorder was played back and the data recorded on a field sheet. Any questionable values were remeasured before leaving the site. Three-dimensional features and general observations concerning the beach and surf characteristics were noted at the time of profiling.

Two tests were conducted to evaluate the operational performance of the articulated frame profiler, one to test its accuracy (closeness to actual value) and another to test its precision (ability to repeat measurments).

Profiling was done alongside a pipe transect and graphical plots of the two were compared, assuming the pipe profile represented true beach elevations. The results, showed a good qualitative relationship, but a poor quantitative representation of the actual beach position.

In the second test, ten profilings were made repeatedly over the same beach transect within the space of an hour. These profiles create a slight envelope when plotted by computer. For the purpose of evaluating the measurements, it was assumed that any of the ten profiles could have been the base profile from which a beach volume change was computed. Volume changes were computed using each of the ten profiles as a base for the remaining nine. This generated 90 volume changes which, when rounded to the nearest cubic meter, had the distribution shown in Fig. 8.

The average distributional is 4.5 m^3, but the distribution shows a peak at 2 m^3 (18 observations or 20%), with two secondary peaks at 3 m^3 and 5 m^3 (14 observations or 15.6% probability), and a tertiary peak at 7 m^3 meters (12 observations of 14.4%). Seventy-five percent of the observations can be expected to be within ± 5 m^3 and 96% within ± 7 m^3 of the actual beach volume change, but there is still a 4% probability of a ± 9 m^3 error. When this inconsistency is added to the natural noise of the system (chance of profiling on the peak or trough of a beach rhythm, or sand loss or gain due to non-storm activity, before and after storm conditions, but within profilings) one would still expect volume changes recorded after storm energy input to be above the noise level. The limitations imposed by sampling error must be recognized in evaluation of the data.

Independent Variables

Tide Data - Observed water levels were obtained from National Oceanographic and Atmospheric Administration (NOAA) tide gauges: a

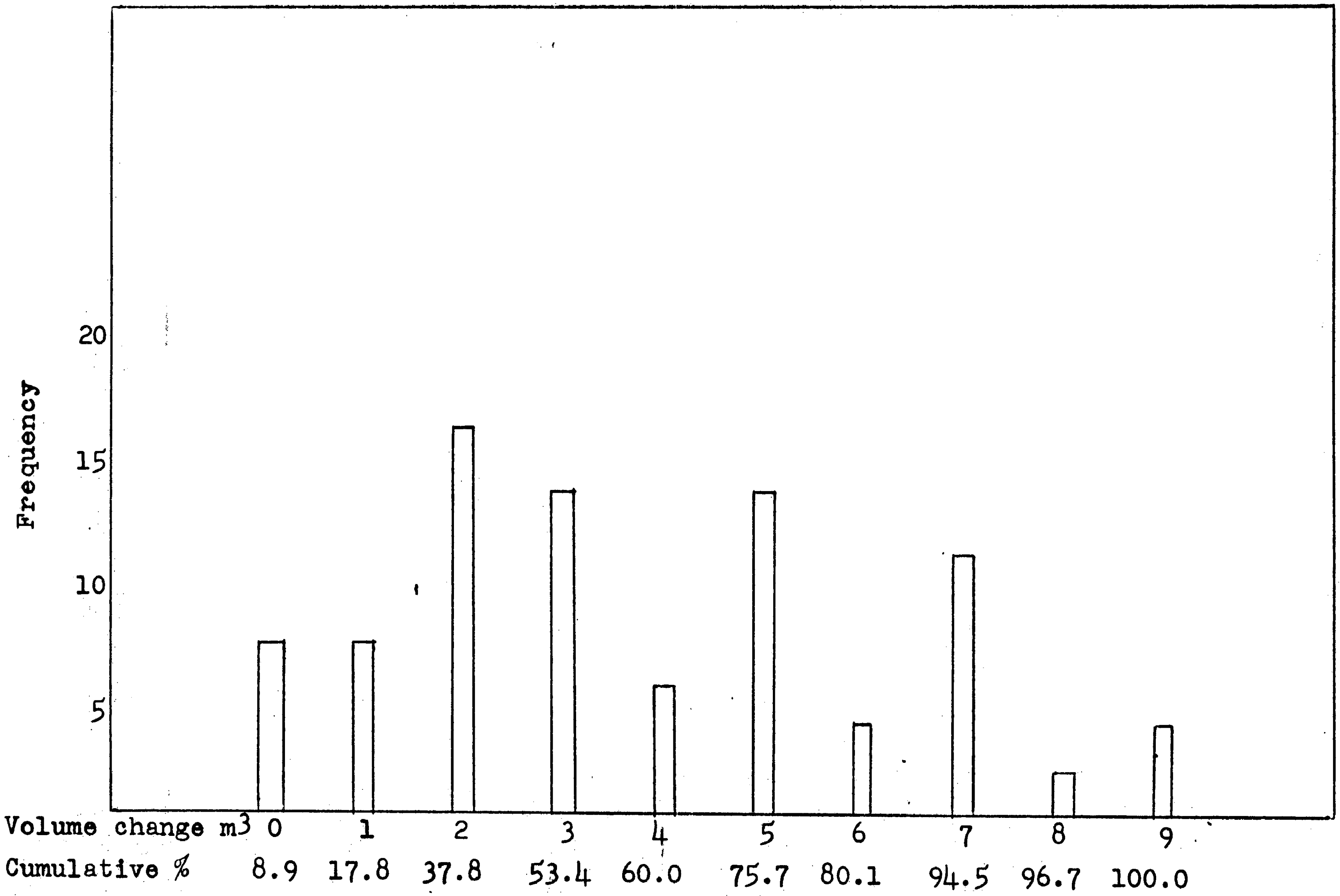


Fig. 8. Expected deviations in volume changes computed from beach profiles.

float-type at Virginia Beach, Virginia and from a bubbler-type located at Wallops Island, Virginia (Fig. 2). Predicted times and water levels for high and low tides were obtained from Tide Tables, East Coast North and South America, Coast and Geodetic Survey, (1969, 1970, 1971). Special computer runs of predicted hourly tides at Virginia Beach and Wallops Island were furnished by the Tide and Tidal Current Prediction section, NOAA.

Wind Data - Wind values were obtained from the National Weather Service in the form of computer printouts from the Six-Layer P. E. (Primitive Equation) Model (for a complete discussion of this model see Shuman and Hovermale, 1968). Wind speed and direction at the 1000-mlb level were recorded for 18 NMC (National Meterological Center) grid points (Fig. 9) at 12-hour intervals for three days prior to profiling. To approximate surface winds, wind speed was reduced to 86% of the 1000-mb value and the direction shifted 20% toward low pressure (Pore and Richardson, 1969). Vector wind components V (+ toward South) and U (+ toward West) were then computed. Reduction of wind data was done by computer (Appendix B).

At various dates wind values were not available for times required, due to computer problems at the NMC. Predicted winds from the P. E. model were then used to supplement the data. This is justified because of the reliability of the P. E. model (Shuman and Hovermale, 1968).

Supplimentary Data -

1. Copies of Ship's Weather Observations (ESSA form 72-1) were obtained for the Chesapeake Light Tower (Fig. 2), located 14 miles east of Cape Henry, Virginia, in 11 m of water. Observations, which were furnished by National Weather Records Center, included wind-wave and swell

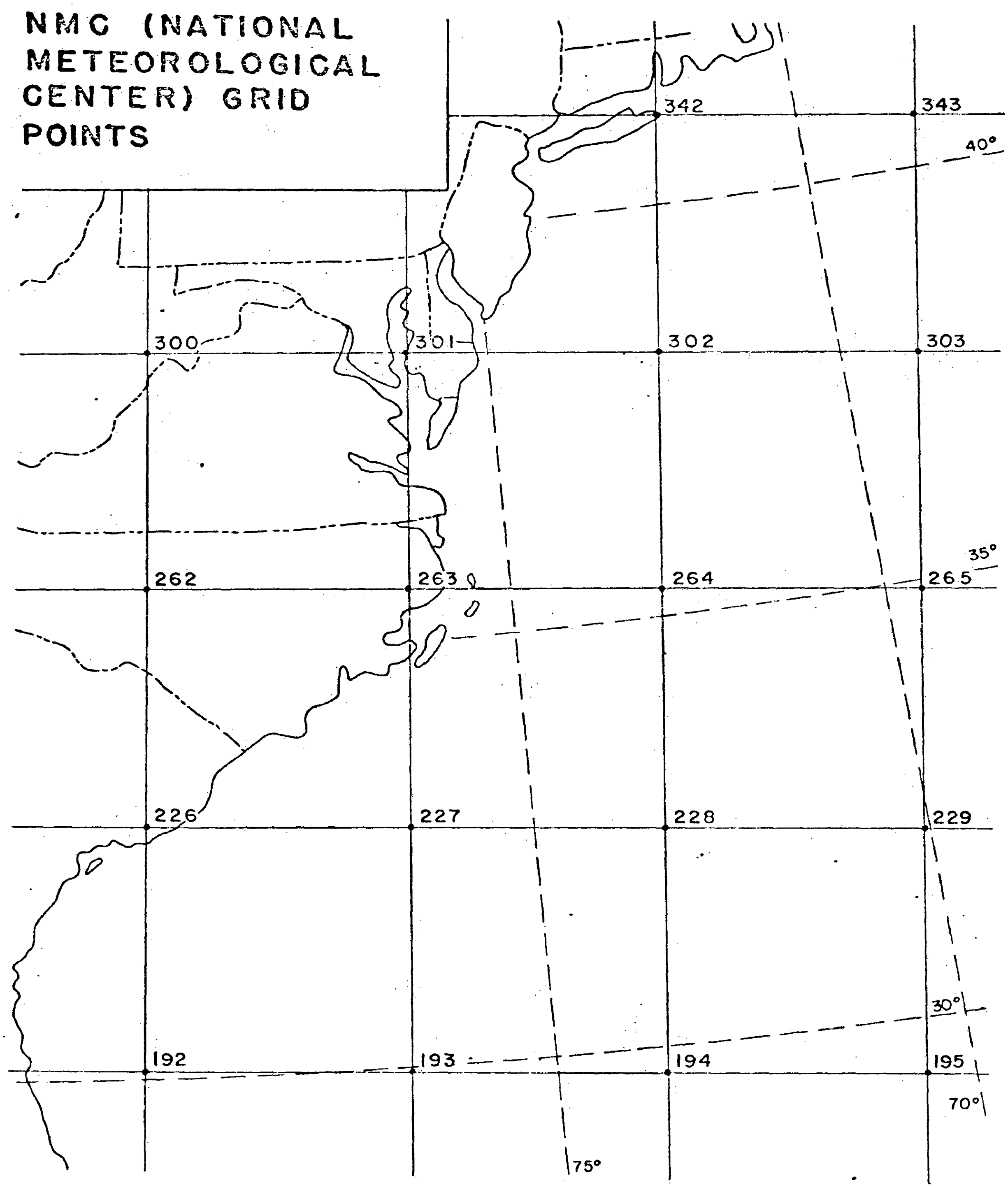


Fig. 9. NMC grid points at which 1000-mb wind values were recorded.

conditions (period, height, and direction), wind speed, sea-level pressure, and general weather conditions.

2. Periodic surveys were made of the profile stations, at which time general beach conditions were noted, and three-dimensional features on the beach were measured.

3. A three-dimensional grid was constructed adjacent to transect 6 (Fig. 2) on Parramore Island. The grid consisted of three parallel pipe transects, perpendicular to the shoreline trend. Successive transects were spaced 8.1 m (½ the wavelength of the beach rhythms present during presurveys), 67 m, and 200 m to the north of profile station 6. Each pipe transect consisted of pipes spaced at 20-m intervals from the base of the dune to the low-tide swash.

Grid data yielded information on variability in the two-dimensional profiles that could be attributed to three-dimensional features moving parallel to the shoreline, and permitted statements as to the representativeness of a single profile line.

4. Sand samples were collected periodically during the profilings. The grain size gradations were measured using a series of Wentworth sieves.

5. <u>Mariner's Weather Log</u>, (U.S. Department of Commerce) and daily weather maps yielded post-storm information as to storm intensity, track, and storm characteristics (wind-waves generated, duration of storm, formation, fetch lengths, scale of disturbance).

The data gathered during the study and used in this analysis will not be included in the manuscript because of the space limitations. Data taken during the study will be available in a report to Coastal Research Center, U.S. Army Corps of Engineers.

FACTORS AFFECTING BEACH CHANGE

What is the feasibility of attempting a forecast of beach volume change in light of present knowledge? King (1959) and Zenkovitch (1967) give thorough summaries of the literature and list the significant variables affecting beach deformation. In summary, these are: beach material, initial beach gradient, bottom character, wave height, wave period, wave steepness, angle of wave approach, still-water-level (swl), and nearshore wind characteristics. The beach water table, first noted by Bagnold (1940), should be added to this list.

Taking these variables one at a time, the following conclusions can be drawn for the purposes of forecasting beach modification during extreme events.

1) Beach material remains fairly constant for a given location. A distribution by grain size and other dynamic properties will be present from the backshore into the offshore zones due to the sorting action of the waves (Miller and Zeigler, 1958). At any given time the nature of the beach material distribution over the beach face depends on the history of the immediate wave regime and water-level. However, the overall beach material distribution is a characteristic of the geology of the area, and for prediction purposes can be assumed constant.

2) Initial beach slope, while shown of considerable importance during the erosion-deposition pattern of a normal tidal cycle (Harrison and Krumbein, 1964), would not be expected to be as critical during storm

conditions. One would not expect the beach to be in or near equilibrium for the wave characteristics that accompany a storm, so any beach slope will undergo deformation. Also, a majority of storm waves are accompanied by a storm surge, which raises the reference plane and transforms the usual foreshore into the nearshore zone. Assuming the slope to be a critical variable in view of the large changes in sand volume, one would expect the initial gradient to vanish early in a storm's history, any beach change, thereafter, attributed to gradient would be directly related to the characteristics of the storm. Analysis of beach gradients for the 16 transects used in the study showed a definite range of gradients for each beach transect, with a strongly concentrated mode (Table 1). Foreshore gradient was distinguished as that incline seaward of the berm of general beach slope break. Initial beach slope was not extensively analyzed in relation to volume changes on the beach, because beach slope effect can be embodied in a broader term, initial beach condition, to be discussed shortly.

3) Bottom character (King, 1959) includes minor bed forms, such as ripples, and more permanent features such as bar systems. One would not expect to notice an effect from anything as transient as a ripple field during major beach modifications, but the effects of a bar system would certainly be felt and would have to be accounted for in any prediction approach.

4) At this point a heretofore unmentioned factor should be included; the initial beach condition or the stage of development from winter to summer beach or vice-versa. This embodies both beach slope, bottom character and grain size as determined by sorting, but more important, it characterizes the volume of sand available for deformation and the

degree to which the beach configuration already matches a storm equilibrium, factors not fully represented by the three previously mentioned beach characteristics.

For a large-sand-prism summer beach, one would expect a much greater sand loss after an eroding storm condition, than from a small-sand-prism winter beach. Indeed, many of the beaches studied could be sufficiently depleted of sand so as to expose an underlying stratum of clay or peat and record no noticeable change, even with very high energy input.

The term will also include any second-order effect of changes in beach material distribution caused by the previously discussed sorting mechanism. Tuck (1969) reports a shift to finer grained sands in the foreshore during eroding storm conditions on a beach within the study area. Any similar change in the nature of the sediment distribution across the beach would be represented by the initial beach condition.

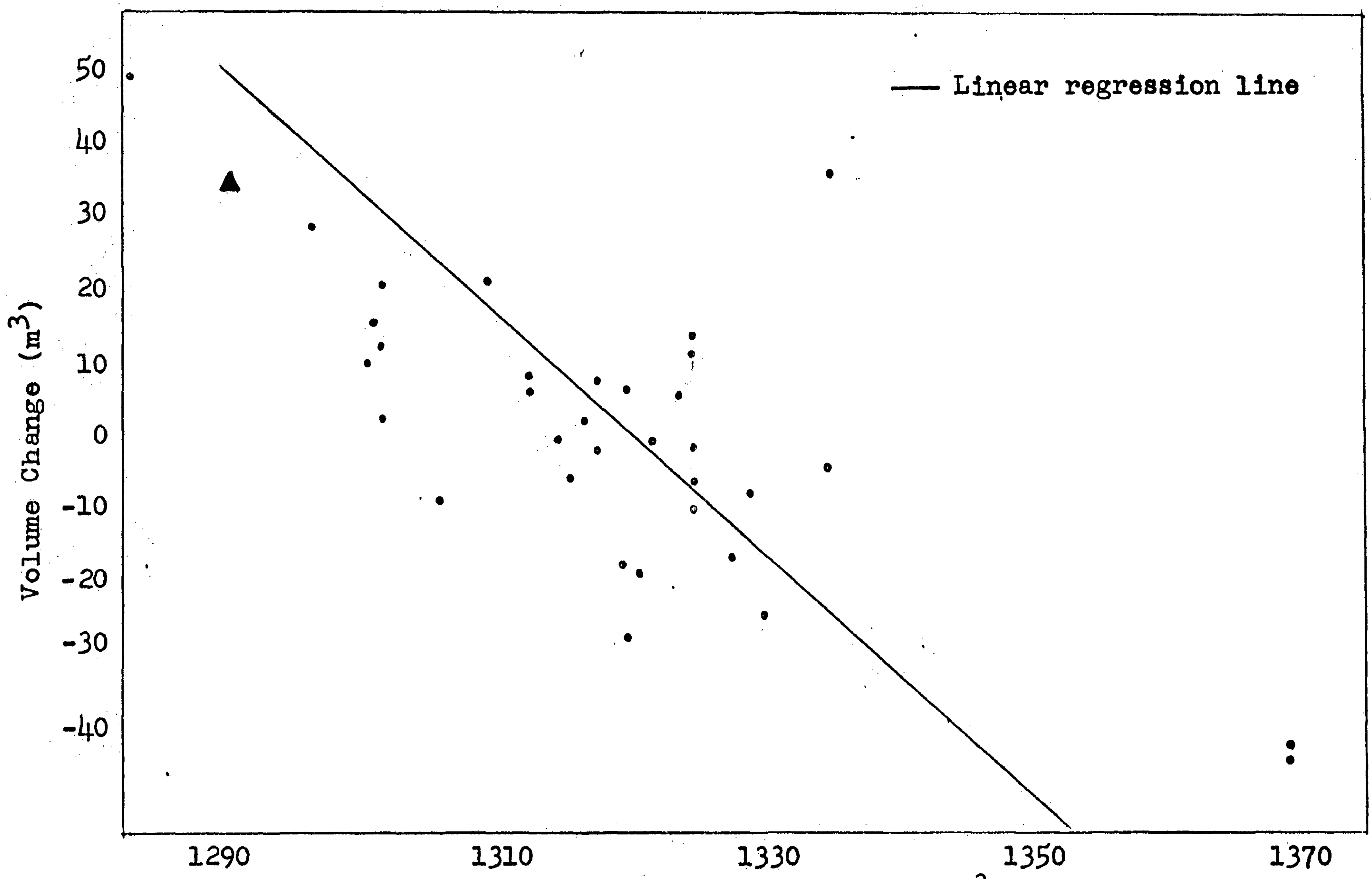
For a given beach, the foreshore gradient is a function of wave activity, but is also dependent on the volume of sand present on the beach. The foreshore is hinged to the backshore, deformation of one is limited by changes in the other. The initial beach foreshore gradient is generally represented within the initial beach condition.

To some degree the initial beach condition also indicates the nature of the surf zone. In the classical winter-summer beach cycle, there is an exchange of sand between the beach and the longshore bars. To the extent that the volume of sand on the beach represents sand lost from the bar system, the initial beach condition will be indicative of the character of the surf zone.

It would seem that the initial beach condition is an important consideration in beach change prediction. To test this rationale, the beach condition was quantified and related to the change in beach sand volume following a storm. The initial beach condition was defined as the amount of sand represented by the area (as seen in cross-section) between a beach profile and an arbitrary base line. Least squares correlation-regression methods were employed, taking the initial beach condition as the independent variable. Linear regression equations were obtained for each of the 16 beach transects, but correlation coefficients were also determined for logarithmic and semi-logarithmic relationships. Table 2 shows the correlation coefficients (r) for the linear regression, and the highest correlation coefficient obtained for each transect, the percentage of explained sum of squares, the slope of the regression equation, the range of sand volume change and the beach length used in the computation of both initial sand volume and volume ch change. Not all of the beaches show a strong relationship, but it is significant that all 16 transects show a negative regression coefficient. The regression for beach transect number 1, Assateague Island (Fig. 3), is shown graphically in Fig. 10. One can see from the data that large beach volume changes only occurred when the beach contained a large sand volume. Intuitively, this would be expected, but it is interesting that if the beach has a low volume of sand, it may accrete during a storm. In this particular example, the beach always built if the sand volume dropped below 1,318 m^3 of sand per unit meter of beach. Some of the accretions were recorded for a short time interval, leaving little doubt that the storm energy was the building factor. A good example for this transect was a 34 m^3 sand volume change (denoted as a triangle on Fig. 10) recorded between September 12 and September 22, 1969. For five

Table 2. Results of correlation-regression of initial beach condition and volume change

Transect	Linear cor coef (r)	Highest cor coef & type	% Explained SS (r^2*100)	Linear regr coef (slope)	Sample size	Range of vol change (m^3)	Prof length (m)
1	-0.69	-0.74 semi-log	55	-0.79	33	80	70
2	-0.68	-0.71 semi-log	50	-0.79	30	45	60
3	-0.40	-0.40 linear	16	-0.33	30	61	50
4	-0.42	-0.42 linear	18	-0.45	35	44	60
5	-0.37	-0.39 semi-log	15	-0.42	45	120	60
6	-0.35	-0.35 linear	12	-0.49	55	52	50
7	-0.45	-0.45 linear	20	-0.38	42	83	70
8	-0.48	-0.49 log-log	24	-0.36	44	102	70
9	-0.28	-0.28 linear	8	-0.20	12	122	70
10	-0.65	-0.65 linear	42	-1.13	7	63	70
11	-0.80	-0.80 linear	64	-1.14	14	33	40
12	-0.51	-0.51 linear	26	-0.50	33	70	50
13	-0.57	-0.60 semi-log	36	-0.63	30	50	65
14	-0.70	-0.70 linear	49	-0.97	28	42	65
15	-0.72	-0.72 linear	52	-0.93	31	49	65
16	-0.70	-0.70 linear	52	-0.99	28	52	65



Volume of Sand on the Beach (m^3)
(cross section between beach profile and base line 20 meters below reference mark)

Fig. 10. Initial beach condition versus beach volume change (transect 1).

days of the 10-day interval, a dry northeaster was present off the coast generating waves of 3.5 m and storm surge of 0.5 m. Other transects showed beach sand accretion of 20-70 m^3 when profilings were taken immediately before and after storm conditions.

There also seems to be an equilibrium point around which sand volume changes of ± 10 m^3 cluster. Admittedly, there is a large amount of scatter in the data. However, considering that no allowance has been made for storm intensity, other than minimum inclusion standards, the results indicate that the initial beach condition exerts a strong influence on beach change.

5) Waves are the predominant energy input into the beach system. Just which wave characteristics (height, period, steepness, power, energy, or other) are of prime importance is still a matter of intense debate, but major importance can be assigned to the waves present.

Here there are some bases for predictions. Numerous methods, both analytical and empirical, are available for forecasting significant waves and wave spectra in either deep or shallow water. Forecasts can be made quickly and fairly accurrately using the Sverdrup-Munk-Bretschneider method (Bretschneider, 1965). Wave spectra are available with a little more effort from the Pierson-Neumann-James method (Pierson, Neuman, and James, 1955). Deep-water wave forecasts are available for the northern hemisphere every 12 hours from the National Weather Service.

6) Wave angle should be segregated from other wave properties. Its independent importance was shown by Harrison (1969). Sonu and Russell (1966) illustrated the dependence of adjacent offshore-foreshore profile covariance on wave angle. When wave fronts approached parallel

to the coast, adjacent profiles reacted similarly and sand exchange occurred between foreshore and nearshore zones; when waves approached at an angle, adjacent profiles did not react similarly. Angle of wave approach is principally related to the causal winds and the bathymetry of the area. Hopefully, angle of wave approach can be treated indirectly from knowledge of these two determining factors.

7) The ocean still-water level, while not imparting energy into the system, is very important. It determines the reference plane from which wave energy will be expended. Simply changing the water-level, assuming no change in wave activity, will cause the beach to undergo a net change. Harrison (1971, written communication) found still-water-level to be very important in determining beach volume changes over a tidal-cycle. Still-water-level is a key factor in determining beach change and must be embodied in any prediction scheme.

Still-water-level can be divided into two components, astronomical tide and the atmospheric-induced disturbance. Atmospheric disturbances, hereafter referred to as storm surge, can be further subdivided into wind set up and the inverted-barometer effect. Information on astronomical tides are readily available. They are predicted on the basis of previously observed tide levels and their precision is dependent on the absence of atmospheric effects from the base observed tide levels. Both numerical and empirical models are available for predicting the storm surge component of water-level (Harris, 1962). Pore (1963, 1964, 1965) has constructed several models with accuracy and reliability well within practical forecasting expectations.

8) Nearshore wind velocity was shown to be important to beach errosion by King (1959) in wave tank experiments. With a strong onshore

wind a surface landward current was generated which created a subsurface seaward return flow. The subsurface flow enhanced the seaward movement of sand grains and increased beach erosion. The presence of a nearshore wind also effected the wave characteristics, increasing the steepness when blowing onshore and flattening the waves when blowing offshore.

Harrison and Krumbein (1964) report that onshore wind speed was apparently a minor causal factor in beach deposition. Whether the explanation is that the wave tank did not adequately mirror natural conditions, or that different beaches respond differently to nearshore wind characteristics, the near shore wind should be included in a beach change forecasting system.

9) Beach water table, while important, has been shown to lag the tide level (Fausak, 1970). A similar effect would be expected during a sizeable storm surge, and for prediction purposes the more easily obtainable oceanic still-water-level can be used.

Summarizing, beach change prediction systems must be concerned with waves, wind, water level, and initial beach conditions. Because winds serve as the energy input for wave formation, it is intuitively sound to simplify the predictors to wind, still-water-level, and initial beach condition parameters. In simplifying and meeting the criteria for functional predictors, causal forces in the immediate vicinity of the beach in question have been omitted from consideration. Atmospheric phenomena are used; these are separated in time and space from the beach environment and must undergo several transformations and energy exchanges, before their momenta and energies emerge at the beach. Either a numerical or empirical model must be employed to follow the energy through the atmosphere-ocean-beach system. An analytical approach would be preferable, but the intricate complexities of the surf zone leave no option.

In constructing an empirical model one of two approaches may be taken:

1) wind, water-level, and initial beach condition can be cast as variables, or

2) wind and water-level can be used as variables and separate equations developed for a range of initial beach conditions.

In either case, knowledge of the initial beach condition would be a prerequisite to beach change prediction. Both wind and water-level are ideal predictors, readily available and easily quantified. However, to correctly characterize the initial beach condition requires a more sophisticated classification system than the crude sand volume indicator used here. In addition, the initial beach condition can be determined only by on-site inspection, in the case of forecasting beach modifications for an entire coastline, this requires considerable time and effort. It would be desirable to ignore the initial beach condition and deal only with wind and water-level. To examine the results obtained from such an approach, an empirical model was tested.

WIND-WATER LEVEL PREDICTION SCHEME

A Proposed Model

Harrison and Pore (1969, written communication) have formulated an empirical predictor equation for forecasting beach changes during extreme events. The predictors chosen are relevant to conditions occurring in the beach foreshore zone, and meet the criteria or routine observation and reliable prediction. The model is as follows:

$\Delta Q_f = f(U_1, V_1, U_2, V_2, \ldots U_n, V_n, W_1, W_2)_{1-6}$, where

ΔQ_f = change in quantity of foreshore sand m^3,

U,V = vector wind components (meters per second) at National Meterological Center (NMC) grid points,

W = ocean still-water-level at a given point (m) relative to a reference elevation,

1-6 = lag times for six successive 12 hour intervals.

This model does not allow for initial beach conditions, but it is desirable to determine the necessity of quantifying initial beach conditions. Also, the model, by nature, assumes that for modeling purposes the offshore zone will act as a constant transform. Given two identical inputs, two identical outputs will emerge at the beach. The validity of this assumption rests with two conditions:

1) that an input does not alter the character of the offshore zone, and

2) that the characteristics of the offshore zone do not change (through some other factor) between the two inputs.

The offshore zone is a highly dynamic area and these conditions are oversimplifying, especially when dealing with the large energy inputs of a storm.

Dividing the offshore zone into two regions, shoaling and surf, the first would be expected to roughly comply with the assumption. Significant alteration of the major bathymetry effecting initial wave shoaling and refraction would not be expected, and could indeed be assumed constant for our purposes. The same cannot be said for the surf.

That major deformation takes place in the surf zone during storm conditions has been demonstrated by Zeigler, Hayes, and Tuttle (1959) and by Sonu and Russell (1966). Sonu and Russell (1966) pointed out the constant exchange of material between the surf and beach proper, to this degree the initial beach condition might reasonably be expected to represent some of the nature of the surf zone. During the present analysis, fully recognizing the dangers involved, both the shoaling and surf zones will be assumed constant.

The model also assumes a two-dimensional beach, where the beach profile at a given transect, is representative of the profile of neighboring transects. To test the validity of this assumption, a series of measurements were taken to determine how well a given beach transect represents the modification of a beach stretch.

A three-dimensional grid was constructed adjacent to profile 6 (Fig. 4). The grid consisted of three pipe transects (discussed in detail in data section), designated 6A, 6B, and 6C and spaced 8.3, 67 and

Table 3. Correlation and regression of adjacent beach transects.

Transects related	Linear Cor Coef (r)	% Explained SS (r^2*100)	Regr Coef (slope)	Separation distance	Sample size
6A and 6B	0.89	79	0.96	67	17
6A and 6C	0.80	64	1.10	267	17
6B and 6C	0.90	81	1.08	200	17

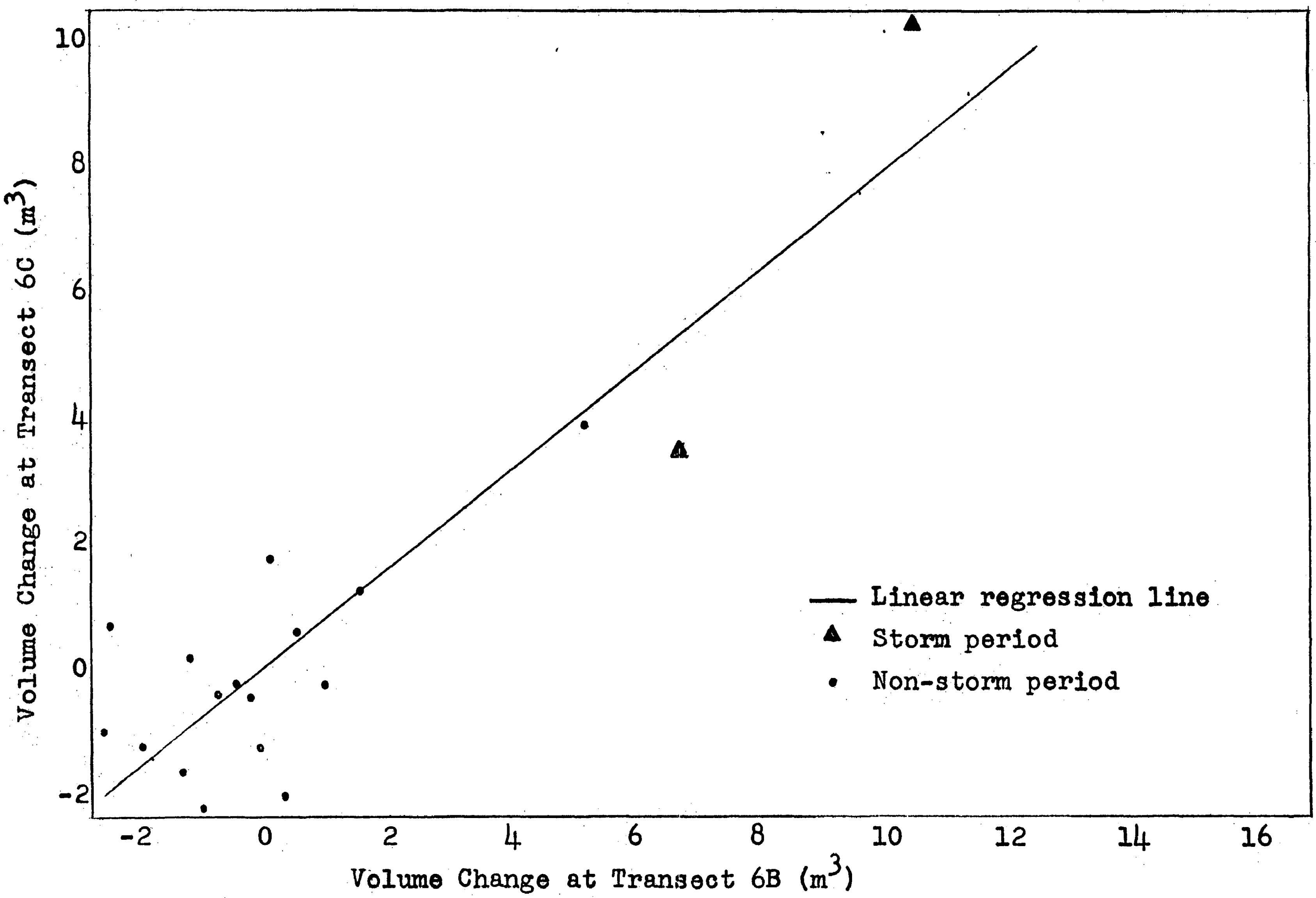


Fig. 11. Relation between adjacent beach transects (6B and 6C).

100 m, respectively, north of transect 6. The grid was sampled at least once a week. The volume changes on each transect were correlated to the other two transects to determine the degree of covariance. As can be seen from Table 3, the correlation between any two transects is quite high. Due to the paucity of storms during the observation period, the majority of transect 6, beach volume changes were within expected error deviations of the articulated frame profiler and were not related to 6A, 6B, or 6C. From the graphical display (Fig. 11), it can be seen that the slope of the regression line is very nearly one. The volume changes during storm conditions are shown as triangles on the graphs.

Covariance between neighboring transects is strongly evident and when treating a given transect as a quarter or half mile section of beach, any deviations would be expected to be within the noise level.

An attempt was made to test this model, hereafter referred to as the Harrison-Pore Model.

Constructing the Model

The approach was to first obtain predictor equations using observed wind and water-level data and then to switch to predicted winds and water-level as input. Water-level was used at tide staff reference, wind values were taken at 1,000-mb level, reduced 86% and shifted 20° toward low pressure (Pore and Richardson, 1969).

A screening procedure was used to empirically fit the Harrison-Pore Model. The method (Harrison, Norcross, Pore and Stanley, 1967, p. 45) is described as follows:

"Basically, the technique is shown below:

(1) $Y = A_1+B_1X_1$

(2) $Y = A_2 + B_2X_1 + C_1X_2$

(3) $Y = A_n + B_nX_1 + C_{n-1}X_2 \ldots NX_n$

where A's are constants and B_1, B_2, C_1, C_2, ect. are regression coefficients.

The procedure is to first select the best single predictor (X_1) for the first regression equation (1). The second regression (2) contains X_1 and the predictor X_2 that contributes most to reducing the residual sum of squares after X_1 is considered.

This procedure is identical to computing partial correlation coefficients between the predicand and each of the remaining predictors, holding the first selected predictor constant and selecting as the second predictor the one giving the highest partial correlation. The third predictor is the one giving the highest correlation coefficient after removal of the effect of the first two predictors; additional predictors are selected in a similar fashion."

The first step was to determine the relative importance of each of 18 selected NMC grid points (Fig. 9) in predicting beach change. Preliminary screening runs for the entire array of grid points indicated that the grid field could be cut to the eleven points numbered: 227, 228, 229, 263, 624, 265, 301, 302, 303, 342 and 343 (Fig. 9).

The second step was to determine lag times. At first, the predictors were lagged from time of profiling, but this procedure proved inconclusive, because the time of profiling depended more on the schedules of the field workers and on access to beaches, after relaxation of high water, than it did upon specific storm characteristics. Lagging for storm intensity seemed more promising and wave regimes were analysed to determine proper lag times.

Wind wave observations at the Chesapeake Light Tower (Fig. 2) were used as an indicator of storm waves traveling toward the coastline. While this approach did not yield specific wave characteristics for given transect locations, wave characteristics at the Light Tower could be taken as indicative of storm intensity. Lag times were determined from the time that the highest waves struck the coast.

Swell observations from the Chesapeake Light Tower were used to limit the NMC grid points used for each lag. Bretschneider (1967) reported that significant wave height is nearly equal to the wave heights reported from visual observations. Using the first order Airy relationship (Ippen, 1966), $C = \frac{gT}{2\pi}$ for wave celerity, travel time of waves can be determined. Since wave period is conserved in shoaling, the deep water condition (group speed equals one half wave celerity) can be applied. The travel distance for a wave of given frequency during a time period can then be calculated using:

d(distance traveled = C_gx t(time of travel)

Using this method, a criterion was developed for inclusion of grid points at specific lags. The distance traveled was not corrected for the fact that group speed approaches individual wave celerity as the waves leave deep water, because most of the distance was under the deep water condition. Two limiting diagrams were developed. The distance waves of periods 1 through 13 seconds (the longest period observed) would travel in a 12-hour period were plotted on a map of the study area (Fig. 12). Another map was constructed for waves of 5-second periods, waves of 5-second periodicity showed a very strong peak in the frequency distribution of storm wave periods. On the second map the distances a wave with a period of 5 seconds could have traveled in multiples of 12-hour intervals was plotted (Fig. 13). From the two maps, one can see that the inclusion of grid point number 343, in a zero lag set of predictors, would not be physically justified. For example, a wave of 9-second periodicity would in theory not travel fast enough to reach the Virginia coast within the first 12 hours following formation. Wave generation time was not considered in the criterion. Allowing for wave

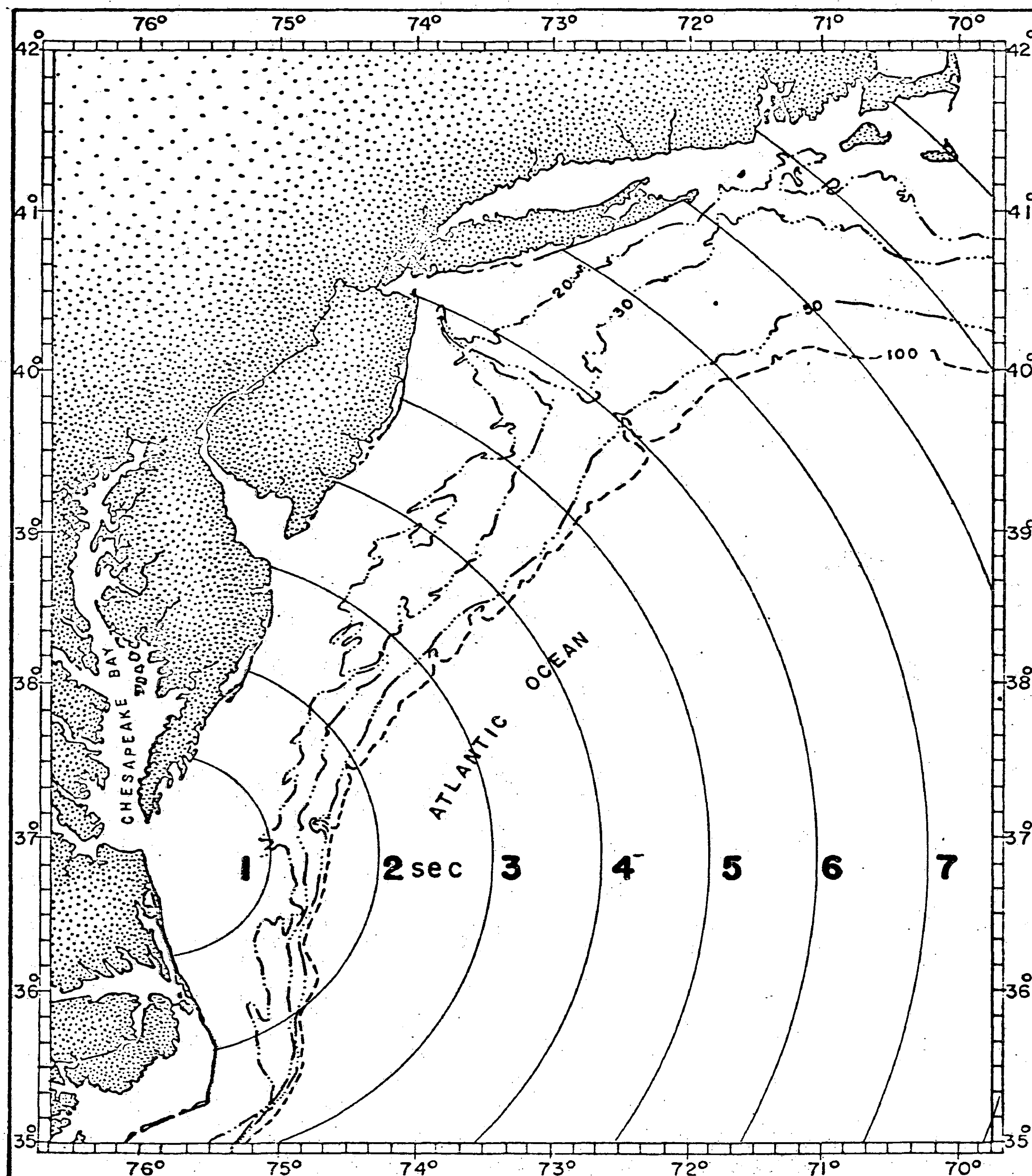


Fig. 12. Distances waves of a given period could have traveled during a 12-hour interval.

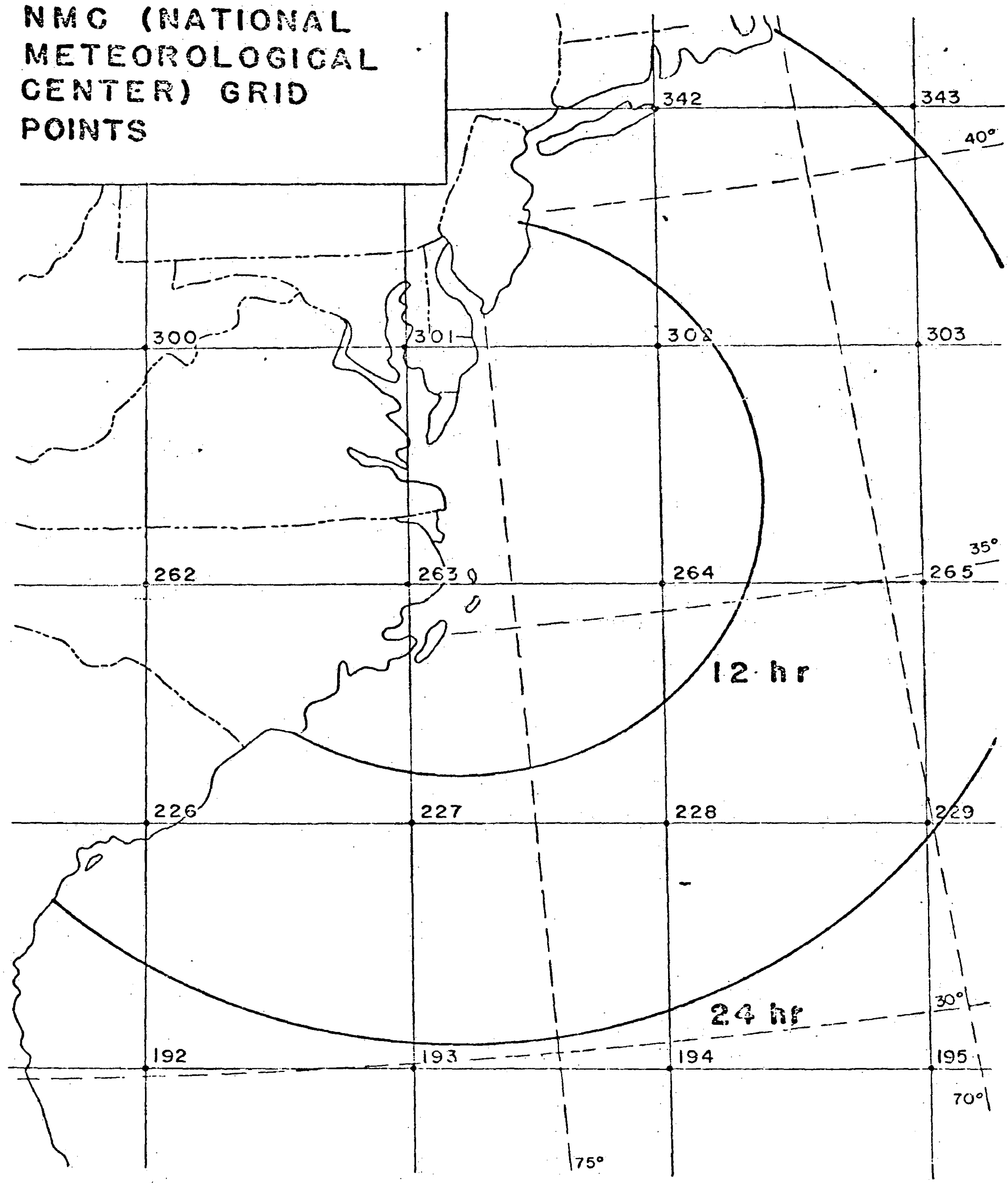


Fig. 13. Distance a wave of 5 second periodicity would travel in 12 and 24 hours.

generation would further increase the time delay between the energy input at a grid point and its appearance at the beach.

Preliminary analysis also called for reevaluation of the water-level parameter. The original model used water-level at Wallops Island and Virginia Beach. These were segregated: Wallops Island for Eastern Shore beaches and Virginia Beach for the six profiles south of Cape Henry. Water-level lags were employed, but showed very little relationship to the beach volume changes. The highest tide level was then used; there was still little relation. This is perplexing at first glance, but in searching the data, we find only one period, two back-to-back storms between March 18 and 20, 1970, with no storm surge; during the remainder of the periods, surges of 1 to 2 feet were consistently present. Highest water-level is, therefore, an almost constant predictor. If the population of sand volume changes were expanded to include beach changes during both storm and non-storm conditions, it would not be surprising to see a significant result.

Once use of the highest tide level had been determined, the question of lagging arose. Should the highest tide level be restricted to a certain time interval prior to profiling, or should it also be lagged to storm intensity as determined by wave heights. Ideally, the highest tide would coincide with the highest wave, but this was not the case. Overlaying tide curves upon curves of maximum wave height versus time yielded no obvious relationship.

Subtracting the astronomical tide, which would not be a function of storm energy from the observed tide, and comparing curves of storm surge versus time with the wave activity curves, no relationship could be distinguished. Wave activity would often peak near a storm-surge peak, but just as often run appreciably ahead or behind the highest water-level during storm activity. As a result, highest tide was taken as the highest water-level during storm activity, and was often somewhat subjective.

An additional predictor, the tidal area factor, was used in preliminary screenings. This factor is defined as the area of the tide curve above mean sea level for a given time period. Three days prior to profiling were used for the calculation. This predictor was dropped when it was not selected by preliminary screening regressions, because it entailed additional data reduction and encoding. In retrospect, this may have been a poor decision, because the tidal area factor showed far greater variability than tide level proper and quantified more individual storm characteristics than mere high water-level. Darling (1964) reported that the duration of the water-level was an important factor in determining what damage could be expected from a storm at Atlantic City, New Jersey. The tidal area factor was discarded on the basis of a very small sample size, part of which were later found in error, and thus this parameter deserves a proper evaluation in future studies.

For final screening regressions, storms were segregated as to severity. This was to some degree a subjective process; however, any storm exhibiting waves two meters or higher, an accompaning storm surge, and yielding a net change in beach sand volume at any transect, was included in the analysis.

Storms were classified into three types: extratropical cyclones, dry northeasters, and hurricanes. In brief, the characteristics of each are given below.

a) Extratropical cyclones are low-pressure centers which form outside the tropics. The storms form through cyclogenesis, usually along a cold front. The winds blow counter-clockwise in the northern hemisphere and the path of the storm is roughly toward the northeast (Byers, 1959).

b) A dry northeaster consists of onshore winds blowing out of a high-pressure cell just after passage of a cold front (Bosserman and Dolan, 1968). There is often confusion between a "northeaster" and a "dry northeaster". A northeaster is an extratropical cyclone that has moved out over the water and is traveling up the coast; a dry northeaster typically moves east and southeast from central Canada.

c) Tropical cyclones, commonly called "hurricanes", form in the tropics and are distinct from the extratropical cyclone previously discussed (Byers, 1959). Deriving their energy from condensation, they are not a product of a frontal system. Winds are more intense and the radius of the storm is typically about one-third that of an extratropical cyclone. Owing to its relatively small diameter, the wind field of a hurricane is not adequately covered by an NMC grid array (Pore and Richardson, 1969). For this reason, hurricanes were excluded from the final screening.

A much more sophisticated storm classification system has been proposed, for storms in the region of the study (Bosserman and Dolan, 1968). It formulates eleven storm types according to origin and movement, factors which affect the characteristics of a given storm. Unfortunately, the present sample size was insufficient to allow such a breakdown, and so the only distinction made was between extratropical cyclones and dry northeasters.

Screening regressions for each of the 16 beach transects were performed with the data arranged according to four criteria:

1) data from both extratropical cyclones and dry northeasters were lumped, and beach volume changes were lagged to the most recent storm in cases of two storms in one profiling interval,

2) data from both storm types were lumped and beach volume changes were lagged to the most intense storm of the interval,

3) only extratropical cyclones were included,

4) only beach volume changes of seven cubic meters or greater and only those volume changes closely associated with a specific storm were considered.

From these iterative procedures it was hoped that critical predictors would be indicated, and several predictor equations developed. However, none of the variables were present in more than two of the volume change prediction equations per screening criterion. This is well within random probability as there were 48 predictors screened and 16 to 30 predictors selected per criterion. Tables 4, 5, 6, and 7 show the prediction equations derived from each screening regression criterion, along with the partial correlation coefficients and the sample size. Failure of the screening regression to repeatedly select one or two key predictors is not in itself invalidating, as there may be little difference between the contributions of many of the predictors. It does, however, indicate that the results should be closely scrutinized.

Perusal of the tables discloses that some of the prediction equations yield relatively high partial correlation coefficients. For example, the prediction equation for transect 3, criterion 2 (Table 5) gives a partial correlation coefficient of .78. However, if we examine the equation it is evident that the screening regression technique has averaged the beach volume changes and discounted the predictors with

Table 4. Results of the screening regression for criterion 1 (data from all storm types lumped, predictors lagged to the most recent storm).

Transect	Predictor Equation	Partial Cor-Coef (r) 1st Term	Partial Cor-Coef (r) Both	Sample Size
1	$\Delta Q_f = -4.14 + 2.02\ U(227)_1 + 0.02\ U(228)_1$	.57	.70	16
2	$\Delta Q_f = -3.99 - 0.83\ V(235)_1 + 0.65\ U(227)_1$	.49	.62	16
3	$* \Delta Q_f = -2.77 - 0.00\ V(263)_2 + 0.74\ V(265)_1$	.68	.80	16
4	$\Delta Q_f = 1.20 - 0.85\ V(301)_1 + 0.68\ V(343)_1$	.44	.58	18
5	$* \Delta Q_f = -2.17 - 0.00\ V(263)_2 - 0.07\ U(263)_2$	.58	.70	19
6	$\Delta Q_f = -0.47 - 0.20\ V(343)_2 + 0.47\ V(265)_1$	.39	.53	19
7	$\Delta Q_f = -5.69 + 1.83\ U(343)_1 - 0.03\ U(229)_2$	.60	.76	18
8	$* \Delta Q_f = -6.61 - 1.69\ V(227)_1 + 0.00\ V(301)_2$	.53	.69	17
11	$\Delta Q_f = -460.87 - 55.84\ W(VB)$	.89		9
12	$\Delta Q_f = -6.65 - 0.07\ V(229)_2 + 1.45\ V(342)_1$	.44	.64	16
13	$\Delta Q_f = -7.90 - 0.12\ V(303)_2 + 1.84\ V(302)_1$	.44	.75	16
14	$\Delta Q_f = 6.21 - 2.21\ U(229)_1 + 1.75\ U(342)_2$	.65	.78	15
15	$\Delta Q_f = 1.54 + 0.04\ U(229)_2 - 1.44\ V(228)_2$	.59	.74	15
16	$\Delta Q_f = 11.60 + 0.11\ U(301)_2 + 0.01\ U(343)_2$	.70	.81	15

* Zero coefficients due to rounding

Table 5. Results of the screening regression for criterion 2 (data from all storms lumped, predictors lagged to the most intense storm conditions).

Transect	Predictor Equation	Partial Cor-Coef (r) 1st Term	Partial Cor-Coef (r) Both	Sample Size
1	$\Delta Q_f = -4.44 + 2.45\ U(303)_2 - 2.37\ V(342)_2$	.45	.70	16
2	* $\Delta Q_f = -5.80 - 1.03\ V(265)_1 - 0.00\ U(265)_2$	.53	.64	16
3	* $\Delta Q_f = 0.06 + 0.00\ V(263)_2 + 0.07\ V(265)_2$	.67	.78	16
4	$\Delta Q_f = 2.22 - 0.82\ V(301)_1 + 0.58\ V(303)_1$	.53	.68	18
5	* $\Delta Q_f = -2.22 - 0.00\ V(263)_2 + 0.06\ U(263)_2$	.58	.70	19
6	* $\Delta Q_f = -1.60 + 0.00\ U(301)_2 + 0.65\ U(343)_1$	.39	.54	19
7	$\Delta Q_f = -6.34 - 1.90\ U(343)_1 - 0.03\ U(302)_2$	.59	.76	18
8	$\Delta Q_f = -8.43 - 1.57\ V(227)_1 - 0.01\ U(264)_2$	.56	.67	17
11	$\Delta Q_f = -5.72 + 0.70\ V(303)_2$	.56		9
12	$\Delta Q_f = -3.65 - 0.06\ U(343)_2 + 1.14\ U(264)_1$	.53	.73	16
13	$\Delta Q_f = 0.85 + 1.90\ U(265)_1 - 0.04\ V(302)_2$	.46	.73	16
14	$\Delta Q_f = -4.57 - 0.14\ U(343)_2 - 0.01\ V(264)_2$	.63	.86	15
15	$\Delta Q_f = 2.61 - 1.50\ V(227)_1 + 0.02\ U(229)_2$	.62	.74	15
16	$\Delta Q_f = 7.27 + 0.10\ U(301)_2 + 2.41\ U(342)_2$	.75	.86	15

* Zero coefficients are due to rounding.

Table 6. Results of the screening regression for criterion 3 (only data from extratropical cyclones used in the sceening).

Transect	Predictor Equation	Partial Coer-Coef (r)	Sample Size
1	$\Delta Q_f = -23.79 - 2.82\ V(228)_1$	.69	12
2	$\Delta Q_f = -8.98 - 1.16\ V(265)_1$	.63	11
3	$\Delta Q_f = -5.57 - 0.90\ V(265)_1$	.52	12
4	$\Delta Q_f = 0.66 - 0.80\ V(237)_1$	.57	11
5	$\Delta Q_f = 5.60 - 3.42\ V(303)_2$	.54	11
6	$*\Delta Q_f = 0.73 + 0.00\ U(265)_2$	.79	11
7	$\Delta Q_f = 7.40 - 0.75\ V(301)_1$	.72	10
8	$\Delta Q_f = -13.51 + 2.30\ U(303)_1$	.72	10
12	$\Delta Q_f = 2.29 - 0.01\ V(342)_2$	.56	10
13	$\Delta Q_f = 5.67\ \ 2.21\ U(264)_2$	.82	10
14	$\Delta Q_f = 8.84 - 1.91\ U(229)_1$	.66	10
15	$\Delta Q_f = 4.48 - 0.12\ V(229)_2$	.81	10
16	$\Delta Q_f = -0.03 - 0.20\ V(302)_2$	.89	10

* Zero coefficient is due to rounding.

Table 7. Results of the screening regression for criterion 4 (only volume changes of 7 m^3 or greater, and volume changes closely associated with a given storm were used in the screening).

Tran-sect	Predictor Equation	Partial Cor-Coef (r) 1st Term	Both	Sample Size
1	$\Delta Q_f = -9.63\ -3.65\ U(227)_2$	.66		13
4	$\Delta Q_f = 1.52\ \ 1.57\ U(227)_2$	.59		9
5	$^{*}\Delta Q_f = -9.33\ -0.00\ V(263)_2\ +2.21\ V(342)_1$	.58	.72	15
6	$\Delta Q_f = -6.09\ -0.08\ U(301)_2$	.70		9
7	$\Delta Q_f = -4.15\ \ 1.91\ U(343)_2$	.70		12
8	$\Delta Q_f = -7.15\ -2.45\ V(227)_1$	.64		12
12	$\Delta Q_f = 9.69\ -0.02\ U(343)_2$	.90		8
13	$\Delta Q_f = -670.42\ -82.74\ W(VB)$	.95		10
14	$\Delta Q_f = 9.46\ -2.17\ U(229)_1$	.70		10
15	$\Delta Q_f = 8.33\ -2.01\ V(264)_2\ +0.23\ V(302)_1$	.62	.77	14
16	$\Delta Q_f = 1.15\ \ 4.02\ U(342)_2$	.61		12

* Zero coefficient is due to rounding.

very small coefficients. This is shown dramatically in a plot (Fig. 14) of actual versus predicted volume change for this transect and prediction equation. The dangers inherent in using the screening regression techniques are clear, and caution must be exercised in drawing conclusions from the results.

On the other hand, many of the predictor equations have predictor coefficients large enough to give considerable weight to the predictors. Transect 14, criterion 1 (Table 4) is a good example of this. The predictor equation gives a partial correlation coefficient of 0.78, identical to that of the previous example (transect 3, criterion 2), but the structure of the prediction equation in this case is very different. A plot (Fig. 15) of predicted versus actual volume change for this example shows a definite trend line. Table 8 gives the predicted and actual beach volume changes and the differences. For the storm conditions tested, the prediction equation forecast a volume change in 56% of the cases that were within the expected deviation of ±7 m^3 of the actual beach change. Only on two occasions, September 22, 1969 and June 14, 1970 (Table 8) were the predicted volume changes grossly misleading. The direction of the beach change was successfully indicated in 69% of the cases. A linear correlation performed for actual versus predicted volume change shows a simple correlation coefficient of 0.77; a similar test of profile 3, criterion 2 yielded a correlation coefficient of -0.16. Testing the prediction equation of transect 14, criterion 1, on a storm not used in developing the equation yields a deviation from predicted of -26 m^3, but the prediction equation indicated the direction of change. Inclusion of the independent storm (shown as a triangle on Fig. 16) reduces the linear correlation coefficient to 0.71. It should be pointed

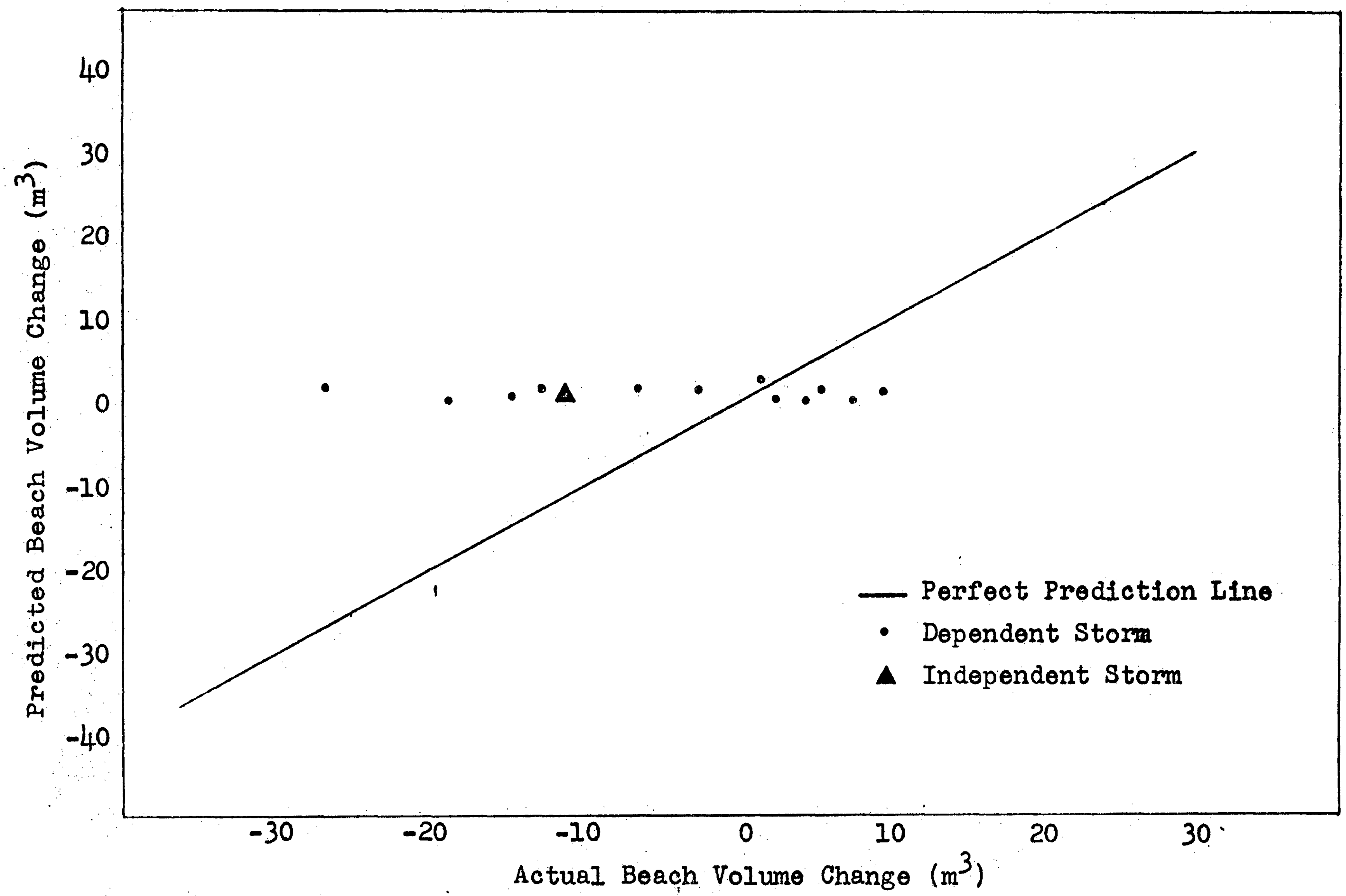


Fig.14. Actual versus predicted volume change transect 3, criterion 2.

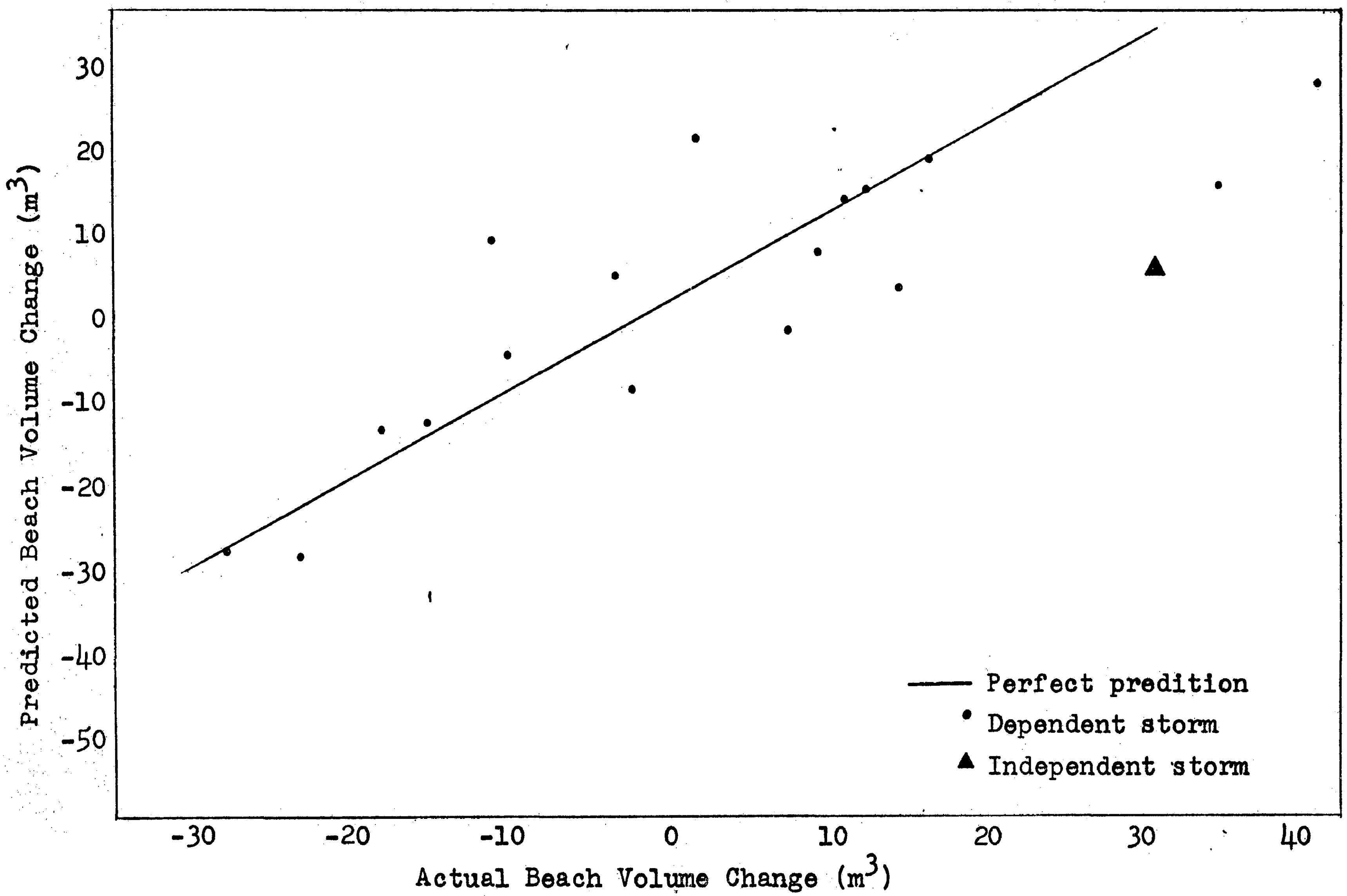


Fig.15. Actual versus predicted volume change, transect 14, criterion 1.

Table 8. Predicted and actual beach volume changes and the differences for transect 14, criterion 1.

Prediction Equation: $\Delta Q_f = 6.21 - 2.21\ U(229)_1 + 1.75\ U(342)_2$

Storm Date mo/da/yr	Predicted Vol Change	Actual Vol Change	Difference (m^3)
8/21/69	-1.63	8.01	9.64
9/22/69	20.67	-2.27	22.94
10/14/69	14.05	12.73	1.32
11/ 3/69	-28.74	-23.11	5.63
12/18/69	26.00	42.42	16.41
2/21/70	-13.66	-18.00	4.33
3/ 7/70	5.37	-2.87	8.24
3/10/70	-9.17	-2.33	6.84
5/ 5/70	-4.75	-10.22	5.46
6/ 9/70	12.75	12.06	0.69
6/14/70	8.03	-11.00	19.03
7/22/70	7.04	9.54	2.49
8/12/70	14.58	36.33	21.74
9/30/70	3.16	4.70	1.53
10/17/70	-13.20	-15.45	2.24
* 12/31/70	30.50	4.93	25.57

* Independent storm (not used in developing prediction eq)

out that the predictors used in this example are a considerable distance from the beach in question, but they do represent the wind pattern expected from an extratropical cyclone centered off the Virginia coast.

There is no guarantee that the prediction equation will apply to storms of another time period, nor that a prediction equation could even be developed for the same profile transect during a different time period. But the predictor equation is strong enough to warrant further investigation.

The sample size of storm induced beach volume changes was very small. If storm characteristics fall into several classifications, segregation as to storm type could enhance the results. Modification of the model to include initial beach conditions could greatly increase the reliability of the predictions. Transect 14, showed both a promising prediction equation and a strong dependence on the initial beach condition. Perhaps the NMC wind values should be altered. The 1000-mb wind values were reduced by 86% and the direction was shifted 20° toward low pressure to approximate surface winds. This procedure was followed on the basis of a study conducted during normal weather activity (Pore and Richardson, 1969). All observations used here were taken during storm conditions, when different pressure distributions would be present. Some other transformation may be more representative of surface winds during storms. The screening regression procedure used assumes a linear relationship between dependent and independent variables. This may be a fallacy, other relationships should be tested. The results of the model as tested suggest that development of prediction equations to forecast sand volume changes may be possible at some beach sites, but for other beach sites the simplified approach used here is inadequate.

INDICATOR BEACH PREDICTION SCHEME

The approach of developing numerous individual models, each tuned to a specific beach site is costly and time consuming. Also, if the initial beach condition proves a necessary input for the prediction model, continuously updated beach measurements will be needed. A prefered approach would be to determine a relation between various transects, and use the predicted beach change at an indicator beach to forecast beach changes at other transects.

It has been demonstrated, for the short time period tested, that in the vicinity of profile 6, it is safe to extrapolate to a half mile. Will this relation hold for greater distances on the same beach or even widely separated beaches? Sonu and Russell's investigation (1966) revealed a relationship when wave fronts approached parallel to the shoreline and a discontinuity when waves approached from an angle. However, they did not investigate the relationship of transect to transect for each angle of wave approach, all angles were aggregated. Also, their data were heavily weighted to average surf conditions and their beach at Nags Head, North Carolina displayed far greater three-dimensionality than did any beaches studied here. An extratropical storm exerts such a dominant and wide-spread influence, that the effects of beach rhythms and tidal cycle deviations would be expected to be within the noise level.

To determine the degree of covariance between beach transects, beach volume changes occurring during the same time period, but from different transects, were related. Ideally, only those volume changes occurring during similar storm conditions should be used, but due to a scarcity of data, storm types could not be segregated.

Least squares-correlation regression methods were used to empirically fit the data to three equations: a linear of form $y = bx+c$, a log-log of form $\lg(y+100) = b \lg(x+100)+c$, and a semi-log of form $y = a^{b(x+100+c)}$. The constant 100 in the log-log and semi-log equations eliminates negative numbers.

Profile 1 through 7A and 11 through 16 were cross-related, Table 9 shows the correlation coefficients. In many cases the sand volume changes produced by several storms had to be aggregated to increase the sample size. This practice did not seem to affect the relationship in any noticeable pattern.

Several of the correlation coefficients are based on sample sizes less than ten, these are designated by an accompanying T. Also, several are based on sample sizes greater than forty and these designated by an F. Relations that showed a preference for log-log or semi-log are designated by an L and S, respectively.

Technically, these data are not candidate for regression. One beach transect has no causal relation to another (except on profiles of Parramore Island and Virginia Beach, where sand lost from one could reasonably be expected to account for sand gained by another, a minor factor). This is strictly a covariance relationship of response to a common causal factor, storm energy input. However, for prediction purposes, fully realizing the violations involved, two transects can be treated as a Model I (no error in X) regression. Assuming an errorless

Table 9.- Correlation Coefficients (r) of the Relation Between Beach Volume Change at Different Transects (T designates sample size less than 10, F designates sample size greater than 40, L signifies log-log relation, S signifies semi-log relation)

Transect	16	15	14	13	12	11	8	7	6	5	4	3	2	1
1	.10LT	.08	.06T	.40LT	.30T	.75LT	.60T	.45L	.06	.08T	.00	.16	.52F	1
2	.30T	.12T	.28T	.46T	.60LT	.47T	.64T	.29L	.35	.30LT	.23	.38T	1	
3	.24T	.50T	.58S	.30ST	.70L	.18T	.70T	.22	.02T	.10ST	.19	1		
4	.63T	.50T	.71T	.40T	.10T	.30T	.21	.72	.44LT	.01	1			
5	.76T	.68L	.44T	.07	.11	.64T	.22F	.30LF	.23F	1				
6	.80T	.06T	.20S	.27	.58	.50T	.41F	.70LF	1					
7	.09T	.25T	.47S	.42S	.17T	.20T	.34F	1						
8	.35S	.78T	.20T	.80T	.26T	.68T	1							
11	.21	.05	.40L	.64	.64	1								
12	.20	.00	.21	.17F	1									
13	.37L	.03	.36L	1										
14	.47	.28	1											
15	.31	1												
16	1													

volume change for a predictor beach, can the volume change on a distant beach be determined?

Selected graphs are shown (Figs. 18, 19, and 20), these are representative of the graphs obtained. Transects 6 and 7 (Fig. 4) are about $1\frac{1}{4}$ miles apart on Parramore Island, 6 and 5 are about $1\frac{1}{2}$ miles apart, but 5 is located on a projection. Transects 1 and 2 are located on adjacent islands.

For prediction purposes the results of these regressions are disappointing. Some show a fair relation, others show very little, and for some, it is clear that no relationship tested is present. When one considers the noise level involved, one can at least discern trends from transect to transect. Several relationships grouped into a compromising general trend are probably present. Zeigler, Hayes, and Tuttle (1958) report that beaches on Cape Cod typically accrete or erode in accordance with particular storm characteristics (angle of wave approach and wind direction). Segregating the data as to storm types could conceivably reduce the scatter.

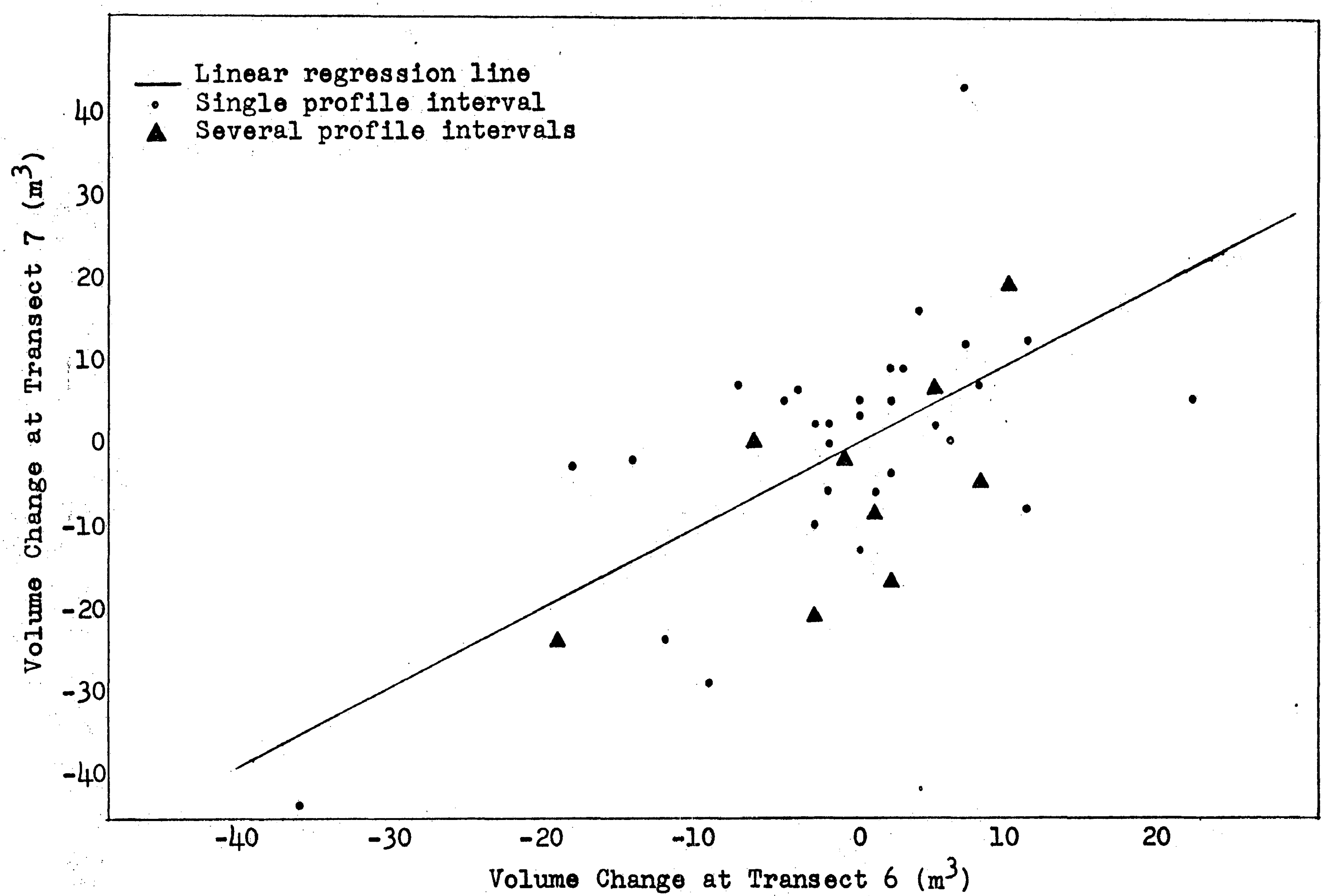


Fig. 16. Relation between volume changes at transect 6 and 7.

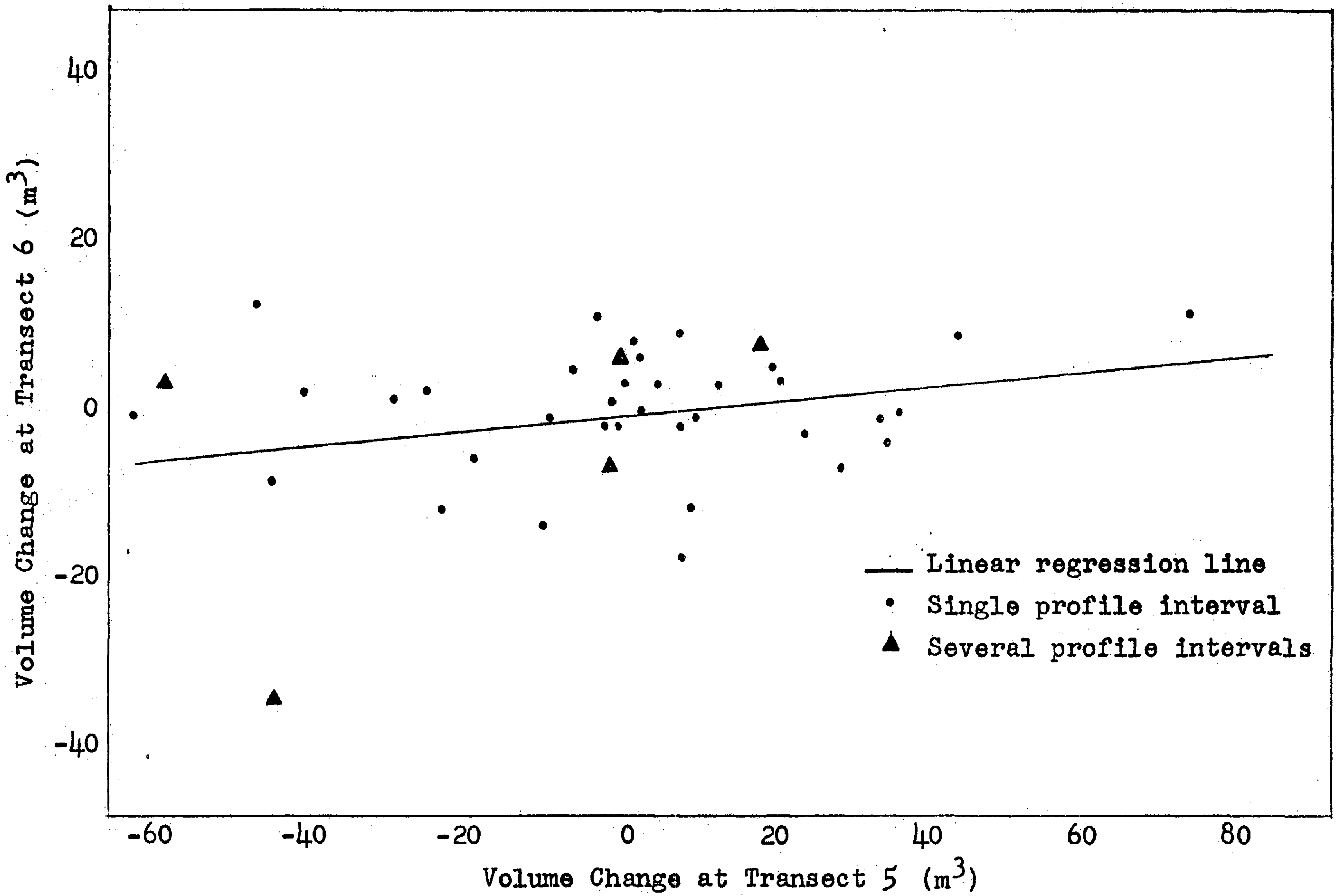


Fig. 17. Relation between volume changes at transects 5 and 6.

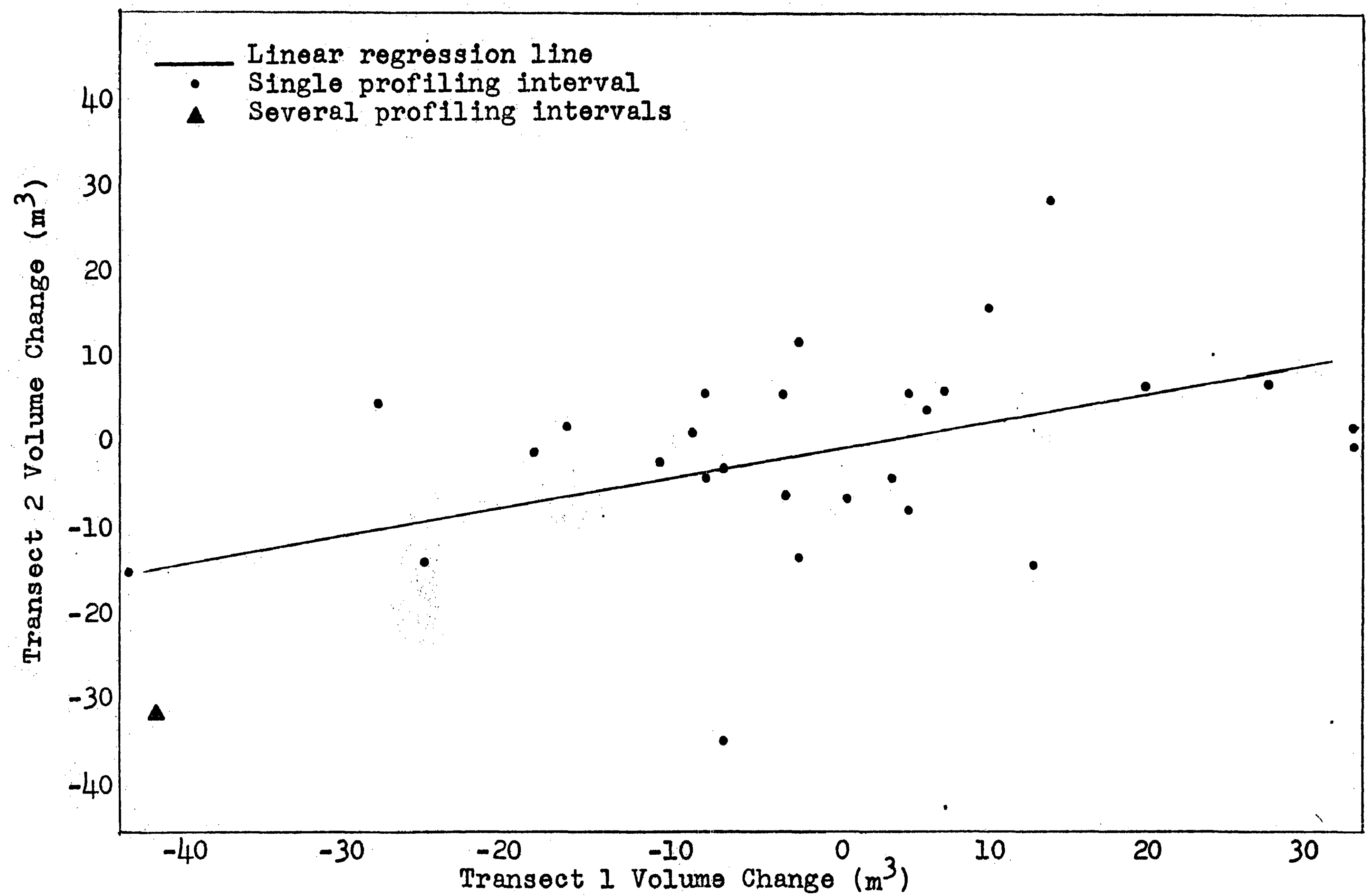


Fig.18. Relation between volume changes at transects 1 and 2.

SUMMARY

In this study, criteria were established for acceptance of variables for use in forecasting beach sand volume changes during storm conditions. Factors known to influence beach modification were examined with an eye to predicting changes in the beach face. Initial beach condition, wind characteristics, and ocean-still-water-level were intuitively felt to be key factors in developing a beach change prediction system. Initial beach volume was shown statistically to be a strong determinant of beach volume change for most beach transects tested. Since knowledge of the initial beach condition requires extensive field measurements before predictions can be made, the initial beach condition was omitted from the empirical model tested.

Empirical equations were developed to predict beach sand volume changes during storm conditions using only wind and still-water-level as parameters. The results are open to dispute, but they indicate that, using longer time periods and more detailed measurements, a prediction equation might be developed for some beach sites.

The relation between sand volume change on one beach and that occuring on a distant beach over the same time interval was investigated. The results indicate that relationships are probably present and it is conceivable that a volume change forecast for an indicator beach may be used to predict the sand volume change on a distant beach.

FUTURE INVESTIGATIONS

One of the most important aspects of the study was that it indicated the areas where further research is needed and demonstrated the problems involved in developing a beach change forecast system, a field where very little work has been done. Future investigations must be concerned with the following:

1) timing of the beach profiles so as to record only storm induced changes in the sand volume,

2) need for greater knowledge of the surf conditions during storm activity,

3) need for fast, accurate beach profilings simultaneously at widely separated locations,

4) development of a meaningful storm classification system in relation to changes induced in the beach-surf system,

5) determination of proper lag times for the predictors,

6) problem of quantifying the initial beach condition; the sand volume indicator used here is crude and unrepresentative of many characteristics that may be present on the beach and a more sophisticated classification system needs to be developed,

7) a similar problem exists in quantifying the surf condition; also, the degree to which the beach condition indicates the surf character needs to be determined,

8) similarities in widely separated beaches need to be examined, and a criteria for classification established,

9) alterations of the Harrison-Pore Model need to be tested, using both new predictors and new transformations on the original predictors, nonlinear techniques should also be tried, and

10) the problem of the small wind field associated with a hurricane must be resolved. A possible solution may be to use the "Energy Index" (Reid, 1957), defined as $R\Delta p$, where R is the radius of the hurricane taken as the distance from the point of lowest pressure (center) to the maximum wind, Δp is the reduction in pressure from normal. The energy index could possibly be used to give a sand volume forecast for beaches in the probable path of a hurricane.

Many more questions need to be explored, but the above seem of immediate concern if progress is to be made in the realm of beach change forecasting.

APPENDIX A

A computer program was developed to compute beach sand volume changes using the polar coordinate pairs of the articulated-frame profiler (see Data section). The use of computer methods in handling this data was essential. Originally the data was reduced by hand. Profiles were graphically plotted and volume changes were determined by a planimeter. Analysis showed this procedure to be grossly in error. The effects of a misplotted angle would accumulate and generate very large deviations. When computer data reduction was instituted, approximately 40% of the hand determined beach volume changes were found to be significantly in error.

The program takes each polar coordinate pair (angle and radius) and transforms these to X,Y rectangular coordinates. Each X,Y pair is then added algebraically to the former X,Y pair. In this manner a complete profile is generated. The program then punches the X,Y coordinates on cards for use in an auxiliary graphing program which plots the beach profile to any scale desired.

After the conversion to rectangular coordinates, the area between the profile and an assumed base is computed. Volume changes are computed as the difference between the area. Volume change cards are punched for use in the screening program.

The program will compute volume changes for any desired profile length and either truncates or extrapolates the profile. The program also edits the data, informing the operator of any questionable values.

The program was written for the IBM 1130 computer. A documented listing of the program is included on the following pages.

```
// FOR
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
*IOCS(CARD,KEYBCARD,TYPEWRITER,1403 PRINTER,DISK)
C PROGRAM ACCEPTS BEACH ANGLE AND BASE LENGTH  POLAR COORDINATE PAIRS
C AND COMPUTES AND PUNCHES X,Y COORDINATES AND BEACH VOLUME CHANGES
C PLACE 99999 CARD AFTER EACH DATA SET, PROGRAM WILL TAKE 50 PROFILES PER RUN
C DEFINITION OF VARIABLES, PROF IS THE PROFILE LENGTH ON WHICH THE VOLUME
C CHANGE IS TO BE COMPUTED, R (RADIUS) AND PHI (ANGLE) ARE POLAR COORDINATE
C PAIRS, X, Y ARE RECTANGULAR COORDINATE PAIRS, LOC AND IDATE DESIGNATE
C LOCATION AND DATE OF PROFILING,AREA IS THE AREA BETWEEN THE BEACH PROFILE
C AND A BASE LINE, VOL IS THE BEACH SAND VOLUME CHANGE, REFHT IS ELEVATION
C OF THE BEACH PROFILE IN REFERENCE TO A BASE MARK, BSLEN IS THE HORIZONTAL
C LENGTH OF THE PROFILE OR THE DISTANCE ALONG THE X AXIS, PROLN IS THE
C ACTUAL LENGTH OF THE PROFILE AS MEASURED, IRNGS IS THE NUMBER OF POLAR
C COORDINATE PAIRS IN A GIVEN PROFILE
      DIMENSION  X(98),Y(98),R(98),PHI(98),LOC(4),IDATE(4),AREA(50),
     1IR(98),   CHEK(20),IDAT2(3,50), ISAV(4),EXT(2),NEXP(50)
      EQUIVALENCE (IR(1),IDAT2(1)),(PHI(1),CHEK(1))
      DEFINE FILE 1(200,320,U,N1)
      DEFINE FILE 2(60,16,U,N2)
      DATA BLANK/'      '/,R(1)/0.0/,PHI(1)/0.0/,EXT/'      ','EXTN'/
      WRITE (1,318)
  318 FORMAT ('DATA SWITCH  0 ON TO BY PASS X,Y PUNCH, DATA SWITCH   1 O
     1N TO BY PASS VOLUME COMPUTATIONS'/     'SWITCH 2 ON TO BY PASS X,Y
     2COORDINATE PRINT OUT'/'HIT START')
      DO 199 I=1,98
  199 IR(I)=I
      PIE=3.14159
  913 N1 1
 1001 WRITE (1,319)
  319 FORMAT ( 'LOAD NEXT DATA SET'              /'IF ALL DATA IN HIT SWITC
     1H 5, HIT START')
      PAUSE
      CALL DATSW (5,ISW)
      GO TO (510,136),ISW
  510 CALL EXIT
C SECTION READS IN COMPLETE DATA SET, PROFFILE LENGTH AND PROFILES
C READS PROFILE LENGTH
  136 READ (2,321) PROF
  321 FORMAT (F8.0)
      WRITE (5,379)
  379 FORMAT ('0'/'0'/'0')
      IF (PROF) 116, 110,1003
C READS ONE PROFLIE, 999 AS RAIDUS SIGNALS THE END OF THE PROFILE
 1003 DO 1002  J1 1,50
      NOK=1
  108 DO 100 J=2,90,8
      J8=J+7
      READ (2,300)(PHI(I),R(I),I=J,J8), LOC,IDATE
  300 FORMAT(8(F5.1,F3.0),4A2,4I2)
C CHECKS SEQUENCE OF CARDS AND COMPARES DATES
      DO 12 I=1,4
      IF (ISAV(I)-IDATE(I)) 109,12,109
  101 IF(IDATE(1)-99) 116,991,116
  116 WRITE (1,304)
  304 FORMAT('SEQUENCE ERROR, OR DATES NOT EQUAL, CHECK THE DECK')
```

```
      PAUSE
      GO TC 108
  109 IF (ICATE(4)-1) 101,12,101
   12 ISAV(I)=IDATE(I)
      ISAV(4)=ICATE(4) +1
C CHANGES ANCLE FRCM POSITIVE DOWN TO POSITIVE UP, SETS RADIUS READ AS
C ZERO TC 1.5 METERS
      DC 100 I=J,J8
      PHI(I)=-PHI(I)
      IF (R(I))127,122,127
  122 R(I)=150.
  127 R(I)=R(I)*.01
      IF (R(I)-1.60) 10C,100,151
  151 IF (R(I)-9.99) 152,102,152
  152 WRITE (1,153) (ICATE(L),L=1,4)
  153 FCRMAT (' BASE LENGTH GREATER THAN 1.5',3I2,3X,I2)
      PAUSE
      GO TC 1001
  100 CCNTINUE
C COMPUTES X,Y CCORCINATES
  102 IRNGS = I-2
      REFHT =-PHI(I)*.01
      JEND  IRNGS&1
      Y(1)=0.0
      X(1)=0.0
      DC 103 I 2,JEND
      RADIN=PHI(I)*2.0*PIE/360.
      X(I)= X(I-1) +R(I)*COS(RADIN)
  103 Y(I)= Y(I-1) +R(I)*SIN(RADIN)
      BSLEN=X(JEND)
      PRCLN=0.0
      DO 350 I=2,JEND
      Y(I)=Y(I)+REFHT
  350 PRCLN=PRCLN+R(I)
      WRITE (1'N1) X,LOC,(ICATE(I),I=1,3),REFHT,BSLEN,IRNGS,PROLN
      WRITE (1'N1)Y
      WRITE (1'N1)R
      WRITE (1'N1)PHI
C PRINTS X,Y COORDINATES IF SWITCH 2 OFF
      CALL DATSW (2,ISW)
      GO TC (1002,451),ISW
  451 WRITE(5,301) LOC(3),LCC(4) ,(IDATE(I),I=1,3)
  301 FCRMAT('OCOORDINATES FOR PROFILE STATION',2A2,'DATE 'I2,'/',I2,'/
     1 ,I2
      L=3
      JEND=(IRNGS/4)*4+1
      DO 106 J 2,JEND,4
      JL=J+L
  106 WRITE (5,302) (IR(I),X(I),Y(I),I=J,JL)
  302 FORMAT(' ',   4(     'C',I2,'=',F5.2,',',F6.2,2X))
      L=IRNGS-JENC+1
      IF(L)     160,160,164
  164 JL=J+L-1
      GC TC (161,162,163),L
  161 WRITE (5,361)(IR(I),X(I),Y(I),I=J,JL)
  361 FCRMAT              (' C',I2,'=',F5.2,',',F6.2,2X)
      GC TC 160
  162 WRITE (5,362)(IR(I),X(I),Y(I),I=J,JL)
  362 FORMAT(' ',   2(     'C',I2,'=',F5.2,',',F6.2,2X))
      GC TC 160
  163 WRITE (5,363)(IR(I),X(I),Y(I),I=J,JL)
  363 FORMAT(' ',   3(     'C',I2,'=',F5.2,',',F6.2,2X))
  160 WRITE (5,303)REFHT,PRCLN,BSLEN
  303 FCRMAT(' PRCFILE IS ',F5.2,' CMS ABOVE ZERO REFERENCE'
     1/' PRCFILE IS ',F7.3,'METERS LONG'/' X-AXIS IS ',F6.2,
     2' METERS LONG')
```

```
 1002 CONTINUE
C SECTION COMPUTES VOL CHANGES
  991 CALL DATSW (1,ISW )
      GO TO (913,912),ISW
  912 NUM=(N1-1)/4
      N1=1
      N2=1
       DO 201 K 1,NUM
      READ (1'N1) X,  LOC,(IDAT2(I,K),I=1,3),REFHT,BSLEN,IRNGS,PROLN
      READ  (1'N1)Y
      READ  (1'N1)R
      READ  (1'N1)PHI
      Y(1)=20.+REFHT
      AREA(K)=0
C IF BASE LENGTH IS GREATER THAN PROFILE LENGTH, PROFLIE IS CHOPPED TO
C PROFILE LENGTH DESIRED, IF BASE LENGTH SHORTER PROFILE IS EXTENDED ON
C BASIS OF LAST THREE ANGLE  OF PROFILE, IF PROFILE IS EXTENDED NEX IS SET
C AT 2 AND  'EXTN' IS PRINTED ON ALL OUTPUT USING THE EXTENDED PROFILE
      IF(BSLEN-PROF ) 230,231,231
  230 AVPHI=(PHI(IRNGS)+PHI(IRNGS-1)+PHI(IRNGS+1))/3.
      NEXP(K) =2
      IF (PHI(IRNGS+1)) 42,42,41
   41 WRITE (5,44) (IDAT2(I,K),I=1,3)
   44 FORMAT(' AREA OF ',I2,'/',I2,'/',I2,'  WAS COMPUTED ON THE BASIS O
     1F A NEGATIVE ANGLE')
   42 I=IRNGS+2
      X(I)=PROF
      RADIN=AVPHI*PIE/360.
      GO TO 205
  231 JEND=IRNGS+1
      NEXP(K) =1
      DO 202 I=2,JEND
      IF(X(I)-PROF)  202,203,204
  202 CONTINUE
  204 X(I)=PROF
      RADIN=PHI(I)*PIE/360.
  205 RAD2=(X(I)-X(I-1))/(COS(RADIN))
      Y(I)=RAD2*SIN(RADIN)+Y(I-1)
C AREA COMPUTED AS THE SUM OF SUCCESSIVE TRAPAZOIDS
  203 DO 201 J 2,I
      Y(J)=Y(J)+20
  201 AREA(K)=AREA(K)+(X(J)-X(J-1))*(Y(J)+Y(J-1))*0.5
      DO 200 K=2,NUM
      VOL=AREA(K)-AREA(K-1)
      IF (NEXP(K)+NEXP(K-1)-2) 208,208,209
  208 NEX=1
      GO TO 207
  209 NEX=2
  207 WRITE (2'N2) VOL,LOC(3),LOC(4),(IDAT2(I,K),I=1,3),(IDAT2(I,K-1),
     1I=1,3),NEX,PROF
      IF(N2-2) 210,210,200
  210 WRITE(5,314)LOC(3),LOC(4),PROF
  314 FORMAT ('0COMPUTED BEACH VOLUME CHANGE PROFILE ',2A2/' VOLUME COMP
     1UTED ON THE BASIS OF A ',F4.0,' METER PROFILE LENGTH'/' VOLUME CHA
     2NGE(SQ M)      DATE (MO/DAY/YR)  SINCE DATE (MO/DAY/YR')
  200 WRITE (5,315) VOL,(IDAT2(I,K),I=1,3),EXT(NEX)
  315 FORMAT (' ',F8.2,4X,I2,'/',I2,'/',I2,4X,A4)
C   SECTION PUNCHS X,Y COORDINATES
  110 CALL DATSW (0,ISW)
      GO TO (911,910),ISW
  910 WRITE (1,511)
  511 FORMAT ('LOAD X,Y COORDINATE CARDS, HIT START')
      PAUSE
      N1=1
      DO 111 K=1,NUM
      READ (1'N1) X,LOC,(IDATE(I),I=1,3),REFHT,BSLEN,IRNGS,PROLN
```

```
      READ   (1'N1)Y
      READ   (1'N1)R
      READ   (1'N1)PHI
  114 READ (2,310) CHEK
  310 FORMAT(20A4)
      DO 112 I=1,20
      IF (CHEK(I)-BLANK) 113,112,113
  113 WRITE (1,311)
  311 FORMAT ('NO BLANK CARD')
      PAUSE
  112 CONTINUE
      WRITE (2,312) IRNGS,BSLEN,PROLN,REFHT,(LOC(I),I=1,4),(IDATE(I),I=1
     1,3)
  312 FORMAT (I2,3X,3(F6.2,3X),32X,4A2,3I2,'1')
      JEND=(IRNGS/5)*5+1
      ISAV(4)=2
      DO 115 J 2,JEND,5
      JL=J+4
  950 READ (2,310) CHEK
      DO 951 I=1,20
      IF (CHEK(I)-BLANK) 956,955,956
  952 WRITE (1,311)
      PAUSE
      GO TO 950
  951 CONTINUE
      WRITE (2,313) (X(I),Y(I),I=J,JL),LOC,(IDATE(I),I=1,3),ISAV(4)
  313 FORMAT (4(2F6.2,1X),2F6.2,4A2,4I2
  115 ISAV(4)=ISAV(4)+1
      JL=J+4
      IF (IRNGS-JEND+1) 111,111,172
  172 JEND=IRNGS+2
      DO 213 I=JEND,JL
      X(I)=0.0
  213 Y(I)=0.0
  954 READ (2.310) CHEK
      DO 955 I=1,20
      IF (CHEK(I)-BLANK) 952,951,952
  956 WRITE (1,311)
      PAUSE
      GO TO 954
  955 CONTINUE
      WRITE (2,313) (X(I),Y(I),I=J,JL),LOC,(IDATE(I),I=1,3),ISAV(4)
  111 CONTINUE
C SECTION PUNCHES VOLUME CHANGES ON CARDS
  911 CALL DATSW (4,ISW)
      GO TO (913,166),ISW
  166 NUM=N2-1
      WRITE(1,320)
  320 FORMAT ('PLACE BLANK CARDS FOR VOLUME CHANGE IN THE HOPPER, TO BY PA
     1PASS THIS SECTION, SWITCH 4 ON,HIT START')
      PAUSE
      N2=1
      DO 400 K=1,NUM
      READ  (2'N2) VOL,LOC(3),LOC(4),(IDAT2(I,1),I=1,3),(IDAT2(I,2),
     1I=1,3),NEX ,PR
  404 READ (2,310) CHEK
      DO 403 I=1,20
      IF (CHEK(I)-BLANK) 401,403,401
  401 NOK=2
      GO TO 113
  403 CONTINUE
  400 WRITE (2,317) VOL,(IDAT2(I,1),I=1,3),PR,EXT(NEX),LOC(3),LOC(4),(ID
     1AT2(I,2),I=1,3)
  317 FORMAT (F8.2,4X,3I2,4X,'PRO LN ',F5.2,A4,1X,2A2,4X,'COMPUTED FROM
     1',I2,'/',I2,'/',I2)
      GO TO 913
      END
```

APPENDIX B

During the study the format of the wind values from the National Meteorological Center (NMC) varied. Wind speed was either in knots or meters per second; wind direction was either direction from which the wind blows or direction toward which the wind blows. To deal with this inconsistency, a subroutine library was developed for use in reduction of the wind data. The mainline program consists simply of a read section, a subroutine section in which the proper subroutines are inserted, a section to round the analyzed wind components (U and V), and a section to punch the vector wind components on cards. Subroutines available are: CORCT (changes wind direction reference to grid north to wind direction referenced to true north), FIX (reduces all directions to less than 360°), REVRS (changes direction from which the wind blows to direction toward which the wind blows), KNOTS (changes wind speed in knots to speed in meters per second), SHIFT (reduces wind speed to 86% of 1000-mb value, and shifts the direction 20° toward low pressure), ANLIZ (breaks wind speed and direction into vector components, U +east and V +south). All subroutines are not used simultaneously, the proper combination is determined by the data format. The system allows maximum flexibility. A documented mainline program and subroutines are included on the following pages.

```
C MAINLINE PROGRAM FOR WIND DATA REDUCTION
// FOR
*LIST ALL
*IOCS(CARD,KEYBOARD,TYPEWRITER,1403 PRINTER,DISK)
*ONE WORD INTEGERS
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
      DEFINE FILE 3(500,40,U,N1)
      DATA M/'M'/,ITWEL/'12'/,IZERO/'00'/, BLNK/'    '/
      ROUND (A)=A+0.5
      CFCTK=1.0/1.942
      N1=1
C SECTION READS CARDS AND CHECKS SEQUENCE
   50 READ(2,1) (D(I),S(I),I=1,7),(ID(I,1),I=1,5),(D(I),S(I),I= 8,14),
     1(ID(I,2),I=1,5),  (D(I),S(I),I=15,18),(ID(I,3),I=1,5)
    1 FORMAT (2(14F5.0,2X,3I2,A1,I1/),8F5.0,32X,3I2,A1,I1)
      IF(ID(1,1)-99)20,60,20
   20 DO 3 I=1,2
      DO 2 J=1,4
      IF(ID(J,I)-ID(J,I+1))100,2,100
    2 CONTINUE
      IF (ID(5,I)-ID(5,I+1)+1)100,3,100
  100 WRITE (1,101)(ID(I,1),I=1,5)
  101 FORMAT ('SEQUENCE ERROR' 3X,3I2,A1,I1)
      PAUSE
      GO TO 50
    3 CONTINUE
      IF(ID(4,1)-M)11,12,11
   11 MOON=ITWEL
      GO TO 51
   12 MOON=IZERO
   51 CONTINUE
C SECTION CALL SUBROUTINES TO MODIFY THE DATA, EXACT TRANSFORMATIONS
C PERFORMED  IS LISTED IN THE SUBROUTINE COMMENT STATEMENTS
      CALL DATSW (1,NIP)
      CALL CORCT
      CALL FIX
      CALL REVRS
      CALL SHIFT
      CALL  KNOTS
      CALL ANLIZ
      DO 52 I=1,18
      IU(I)= ROUND(U(I))
   52 IV(I)= ROUND(V(I))
      WRITE (3'N1) IU,IV,(ID(I,1),I=1,3), MOON
      GO TO (53,50),NIP
   53 WRITE (5,650)
  650 FORMAT ('0' 20X 'ROUNDED  U   AND   V  COMPONENTS')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('   192    193    194    195    226    227    228    229    262    2
     163    264    265    300    301    302    303    342    343')
      WRITE(5,903)
  903 FORMAT(' ' 'U  (NORTH-SOUTH)')
      WRITE (5,901)IU
      WRITE(5,904)
  904 FORMAT (' ' 'V  (EAST-WEST)')
      WRITE (5,901)IV
  901 FORMAT(' 'I4,17I6)
      WRITE (5,905)
  905 FORMAT ('0'/'0')
```

```
      GC TC 50
C SECTICN PUNCHES RCUNCEC U, V WIND COMPONENTS CN CARDS
   60 K=N1-1
       N1=1
      DC 500 L=1,K
      REAC  (3'N1) IU,IV,(IC(I,1),I=1,3), MOON
   31 REAC (2,5) CHK
    5 FCRMAT (20A4)
      DC 10 I=1,20
      IF (CHK(I)-BLNK) 15,10,15
   10 CCNTINUE
      WRITE(2,16)(IU(I),IV(I),I=1,10),(ID(I,1),I=1,3),MOON,(IU(I),IV(I),
     1I=10,18),(IC(I,1),I=1,3),MCCN
   16 FCRMAT (20I3,3X,'WIND 1',3X,3I2,A2/18I3, 9X,'WIND 2',3X,3I2,A2)
      GC TC 500
   15 WRITE(1,30)
   30 FCRMAT(' NC BLANK')
      PAUSE
      GC TC 31
  500 CCNTINUE
      CALL EXIT
      END


C SUBRCUTINE REVRS CCNVERTS DIRECTION TOWARD WHICH THE WIND BLOWS TC
C THE DIRECTICN FRCM WHICH THE WIND BLOWS
// FOR
*LIST SCURCE PRCGRAM
*ONE WORC INTEGERS
      SUBRCUTINE REVRS
      CCMMCN C(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MCCN
      DC 400    I=1,18
      IF (C (I)-180.) 4C1,4C1,4C2
  401 D(I)=C(I)+180.0
      GO TC 4C0
  402 D(I)=C(I)-180.0
  400 CCNTINUE
      GC TC (1,2),NIP
    1  WRITE(5,43C)
  430 FCRMAT ('0' 2CX 'TRUE DIRECTICN FROM WHICH THE WIND BLOWS')
      WRITE (5,902)(IC(L,1),L=1,3),MOON
  902 FCRMAT(I3'/',I2'/',I2,5X,A2,'OOZ')
      WRITE (5,90C)
  900 FCRMAT ('  192   193   194   195   226   227   228   229   262   2
     163   264   265   300   301   302   303   342   343')
      WRITE (5,901)C
  901 FCRMAT(' ' 18F6.1)
    2 RETURN
      END
```

```
C SUBROUTINE CORCT CHANGES THE DIRECTION REFERENCE TO GRID NORTH TO
C DIRECTION REFERENCED TO TRUE NORTH
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE CORCT
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
      D(2)=D(2)+3.2
      D(3)=D(3)+6.3
      D(4)=D(4)+9.5
      D(6)=D(6)+3.4
      D(7)=D(7)+6.7
      D(8)=D(8)+10.0
      D(10)=D(10)+3.6
      D(11)=D(11)+7.1
      D(12)=D(12)+10.6
      D(14)=D(14)+3.8
      D(15)=D(15)+7.6
      D(16)=D(16)+11.3
      D(17)=D(17)+8.1
      D(18)=D(18)+12.1
      GO TO (1,2),NIP
    1 WRITE (5,102)
  102 FORMAT('0' 20X 'TRUE DIRECTION TOWARD WHICH THE WIND BLOWS')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('   192    193    194    195    226    227    228    229    262    2
     163    264    265    300    301    302    303    342    343')
      WRITE (5,901)D
  901 FORMAT(' ' 18F6.1)
    2 RETURN
      END


C SUBROUTINE KNOTS CONVERTS SPEED IN KNOTS TO METERS PER SECOND
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE KNOTS
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
      DO 200       I=1,18
  200 S(I)=S(I)* CFCTK
      GO TO (1,2),NIP
    1 WRITE(5,201)
  201 FORMAT('0'20X 'VELOCITY IN METERS PER SECOND')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('   192    193    194    195    226    227    228    229    262    2
     163    264    265    300    301    302    303    342    343')
      WRITE (5,901)S
  901 FORMAT(' ' 18F6.1)
    2 RETURN
      END
```

```
C SUBROUTINE ANLIZ BREAKS SPEED AND DIRECTION INTO U,V COMPONENTS
// FOR
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
      SUBROUTINE ANLIZ
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
       DO 500   I=1,18
      PHI=D(I)
      IF (PHI-90) 501,501,502
  501 U(I)=-S(I)*COS(PHI*3.14159/180.0)
      V(I)=-S(I)*SIN(PHI*3.14159/180.0)
      GO TO 500
  502 IF (PHI-180.) 503,503,504
  503  PHI=180.-PHI
      V(I)=-S(I)*SIN(PHI*3.14159/180.0)
      U(I)= S(I)*COS(PHI*3.14159/180.0)
      GO TO 500
  504 IF (PHI-270.) 505,505,506
  505  PHI=PHI-180
      V(I)= S(I)*SIN(PHI*3.14159/180.0)
      U(I)= S(I)*COS(PHI*3.14159/180.0)
      GO TO 500
  506  PHI=360.-PHI
      U(I)=-S(I)*COS(PHI*3.14159/180.0)
      V(I)= S(I)*SIN(PHI*3.14159/180.0)
  500 CONTINUE
      GO TO (1,2),NIP
    1 WRITE (5,550)
  550 FORMAT('0' 20X 'ANALIZED  U  (+NORTH) AND  V  (+EAST) VECTOR COMPO
     1NENTS')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('  192   193   194   195   226   227   228   229   262   2
     163   264   265   300   301   302   303   342   343')
      WRITE(5,903)
  903 FORMAT(' ' 'U  (NORTH-SOUTH)')
      WRITE (5,901)U
      WRITE(5,904)
  904 FORMAT (' ' 'V  (EAST-WEST)')
      WRITE (5,901)V
  901 FORMAT(' ' 18F6.1)
    2 RETURN
      END
```

```
C SUBROUTINE SHIFT REDUCES SPEED TO 86  OF THE 1000 MILLIBAR VALUE AND
C SHIFTS THE DIRECTION 20 DEGRESS TOWARD LOW PRESSURE
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE SHIFT
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
      DO 300    I=1,18
  300 D(I)= D(I)-20.0
      DO 301 I=1,18
  301 S(I)=S(I)*.86
      CALL DATSW (1,NIP)
      GO TO (1,2),NIP
    1 WRITE (5,310)
  310 FORMAT('0' 20X, 'SPEED (86 PERCENT) AND DIRECTION (SHIFTED 20 DEGR
     1EES TOWARD LOW PRESSURE)')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('  192   193   194   195   226   227   228   229   262   2
     163   264   265   300   301   302   303   342   343')
      WRITE(5,903)
  903 FORMAT ('OVELOCITY')
      WRITE (5,901)S
      WRITE(5,904)
  904 FORMAT ('ODIRECTION')
      WRITE (5,901)D
  901 FORMAT(' ' 18F6.1)
    2 RETURN
      END


C SUBROUTINE FIX CHECKS THE WIND DIRECTION AND REDUCES  THOSE GREATER
C THAN 360 DEGRESS TO  THE PROPER DIRECTION BETWEEN  ZERO AND 360 DEGREES
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE FIX
      COMMON D(18),S(18),U(18),V(18),IU(18),IV(18),ID(5,3),CHK(20),NIP,
     1CFCTK,MOON
      DO 700 I=1,18
      IF(D(I)-360.) 700,700,702
  702 D(I)=D(I)-360.0
  700 CONTINUE
      GO TO (1,2),NIP
    1 WRITE(5,701)
  701 FORMAT ('0' 20X 'DIRECTION (ZERO TO 360 DEGREES)')
      WRITE (5,902)(ID(L,1),L=1,3),MOON
  902 FORMAT(I3'/',I2'/',I2,5X,A2,'00Z')
      WRITE (5,900)
  900 FORMAT ('  192   193   194   195   226   227   228   229   262   2
     163   264   265   300   301   302   303   342   343')
      WRITE (5,901)D
  901 FORMAT(' ' 18F6.1)
    2 RETURN
      END
```

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